

**The effects of magnesium fertiliser and grass on  
the nutrition and growth of *P. radiata*  
planted on pumice soils in the  
Central North Island of  
New Zealand**

a thesis  
presented for partial fulfilment of the degree  
of  
Doctor of Philosophy in Forestry  
in the  
University of Canterbury  
Christchurch, New Zealand

by  
**Timothy William Payn**  
1991

FORESTRY

~~THESIS~~

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1991

## Dedication.

To my mother Barbara,  
my wife Barbara,  
and my daughter Katherine Barbara.

Thanks!

## Abstract.

This thesis addressed the problem of the widespread occurrence of magnesium deficiency in *Pinus. radiata* planted on pumice soils in the central North Island of New Zealand, the increased severity of the deficiency where trees were planted on grassed sites, and the slow increase in foliar Mg concentrations and tree growth following fertilisation of deficient trees with various sources and rates of Mg fertiliser.

Plant available Mg concentrations were found to be very low in pumice soils, with soil solution concentrations often below  $1 \text{ mgL}^{-1}$  and exchangeable concentrations in the upper 20 cm of the soil normally well below  $1 \text{ meq100g}^{-1}$ . Published soil critical levels for a number of crops fall into the range of 0.2 to  $1.0 \text{ meq100g}^{-1}$ . Addition of between 100 and  $400 \text{ kg ha}^{-1}$  Mg (as Epsom salts, dolomite, or calcined magnesite) in a laboratory study raised soil solution concentrations by between 8 and  $37 \text{ mgL}^{-1}$  and exchangeable concentrations by between 1.5 and  $3.4 \text{ meq100g}^{-1}$ . These levels should be adequate for tree growth. Epsom salts caused a much greater increase in solution Mg concentration than either dolomite or calcined magnesite.

Changes in soil solution and exchangeable concentrations were monitored in a field experiment. Epsom salts and calcined magnesite were added at  $400 \text{ kg ha}^{-1}$  Mg. The Epsom salts caused a large and rapid increase in solution Mg concentrations to a soil depth of at least 45 cm. Calcined magnesite had no significant effect on solution concentrations. Both treatments increased exchangeable Mg concentrations well above  $1 \text{ meq100g}^{-1}$ , although the less soluble calcined magnesite was slower acting. Improvements in exchangeable Mg were still apparent after 18 months with concentrations of the order of  $1.5 \text{ meq100g}^{-1}$  in the upper 20 cm, although soil solution concentrations had returned to pre-fertilisation levels.

The effects of Mg deficiency on dry matter allocation patterns were investigated in a glasshouse and a field experiment. Mg deficiency caused a 25% decrease in root:shoot ratio in seedlings. In an 8 year old stand of trees, where above ground dimensions were the same, but foliar concentrations were above or below the critical level of 0.07% Mg, there was 50% less fine root length in the deficient trees when compared to the healthy. This root decline could explain the slow response of fertilised trees, either due to a smaller exploitable soil volume, or due to a need to rebuild the root system before a response is detectable above ground.

Two field experiments using  $400 \text{ kg ha}^{-1}$  Mg as Epsom salts were established, one in a newly planted area (Halls), and the other in an 8 year old Mg deficient *P. radiata* stand (Kiorenu). At this high rate foliar Mg concentrations were improved to well above 0.1% within six months of Mg application. This indicated that previous slow responses were likely to have been due to use of low rates or slowly soluble sources of Mg. No growth responses were recorded in either trial, the juvenile trees were only marginally deficient by age 3, and the older trees were measured only six months after fertiliser application.

Foliage analysis and tests with a total spectrum fertiliser indicated no other elements were deficient in either of the field experiments.

The effect of grass on tree growth and Mg uptake was tested at Halls in the juvenile trees. Removal of grass competition caused a 30% improvement in tree biomass at age 3, 18 months after

treatments were applied. Grass competition intensified the Mg deficiency in the trees and if trees were fertilised without grass control, tree growth was slightly suppressed due to stimulation of the grass. It was suggested that this was an effect on the soil moisture conditions and hence nutrient uptake rather than a direct effect of the grass in competition for Mg.

The Barber-Cushman nutrient uptake model was used for a sensitivity analysis of parameters affecting Mg uptake on the newly planted site. This showed that root growth and Mg influx parameters were most important on this site, suggesting that Mg supply was not limiting growth, a conclusion supported by the fertiliser experiment results. Calculation of Mass Flow Coefficients indicated that far more Mg would be supplied to the root than would be assimilated by the tree.

Calculation of Mass Flow Coefficients from published data for an age range of *P. radiata* up to age 12 showed that on a site with low soil solution Mg concentration ( $0.3\text{--}0.5\text{ mgL}^{-1}$ ), once the trees were older than 3 years the proportion of Mg supplied to the root by diffusion increased until by age 5 approximately 75% would be supplied by that means. The importance of soil diffusion rates and soil moisture conditions will therefore be greater for older trees. A soil solution concentration of  $1\text{--}2\text{ mgL}^{-1}$  was calculated to be the level at which 100% of Mg would be supplied by mass flow, and this could be used for identifying potentially deficient sites.

Conclusions from this study, plus other published information on the topic were synthesised into a set of rules. These will be the basis of an expert system for managing the Mg nutrition of *P. radiata*.



## Acknowledgements.

This project has been a very enjoyable and stimulating experience, made more so by the support of a great number people and Institutions. The project was organised through the National Forest Fertilising Co-operative, and I would like to acknowledge the support of the Co-operative, and specifically Tasman Forestry Ltd. David New of that company was instrumental in setting things up, and Wayne Smith was closely involved throughout the 3 years. In the early stages Dave Sayer and Shaylene Robertson of the Taupo office were involved in the establishment of the Halls trial. A special mention must go to Paul Stevens, also of the Taupo office, without whom Chapter 3 would probably still be an idea. He conscientiously took the monthly lysimeter samples and kept an eye on the trial (I was in Christchurch, the trial was in Taupo, 700 km away!). Thanks also to various other Tasman staff for help in other ways. Owen and Margaret Woodham always made me welcome in Taupo and fed me the occasional trout.

During the three years I received much support from people at the Forest Research Institute, both in Rotorua and Ilam. In Rotorua David Whitehead helped me enormously with aspects of plant water relations and initiated me into the complexities of stomatal conductances and photosynthesis measurements, a fascinating topic which I unfortunately did not use in the detail I would have liked. I had most enjoyable discussions with Peter Beets on various aspects of tree growth and magnesium problems of radiata pine, and he very kindly gave me access to unpublished data on Mg uptake in an age range of trees. I would like to thank Jean Prince, Liz Weatherby, and Helene Beeser for assistance with various analytical aspects. Doug Graham lent me the keys to the fertiliser store, and Jessica Hunter and Christine Mees helped with final editing.

At Ilam Peter Clinton was always keen for a yarn, and helped me keep things in perspective. Murray Lang ran samples through the Atomic Absorption faster than the eye could blink, and Murray Davis lent me his centrifuge tubes. Graeme Rogers was very helpful when I was trying (unsuccessfully) to get results from Mg depletion experiments in the growth chambers.

At the School of Forestry I would like to thank all the technical staff for help along the way, but especially Krisi Posthuma for great help in the glasshouse. Vicki Mackisack and Jeanette Allen in the office, always cheerful, kept me in the same frame of mind. During the latter stages of the project I had invaluable help from Karen Ming-Wong and Gerhard Hunner during and after the biomass sampling, and Peter Ndegwa helped with that and an earlier root sampling exercise.

I also would like to acknowledge the support I received in 1990 from the Northern Southland Farm Forestry Association, and also during 1990 and 1991 from the Trustees of the Holt Forest Trust, who supported both the project and myself. The University of Canterbury also supported the project, the purchase of a laptop computer was a lifesaver, with field sites around Taupo and a base in Christchurch.

I was very fortunate to have three outstanding advisers on the project. Graham Will was the first person to identify Mg deficiency in *P. radiata* in New Zealand, back in the late 1950s. His encyclopedic knowledge of the history of the problem, the region, and the nutrition of *P. radiata* helped immensely. Ian Hunter had also worked extensively with Magnesium and *P. radiata* and this project was able to build on a number of his findings. I am grateful for his skills as a facilitator, things ran very smoothly. Finally my main adviser, Don Mead let me get on with it, and with his experience with experimental design and writing skills helped craft a better thesis.

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# Chapter 1

## Background to magnesium problems in *P. radiata* in New Zealand

### INTRODUCTION

In their summary of the exotic forests planted in New Zealand, Collins *et al.* (1988) quoted the total area planted to be 1,154,226 hectares. Of this, approximately 498,000 ha, or slightly over 40% of these forests are planted on Central North Island sites underlain by soils derived from pumiceous deposits. The bulk of these plantings are in the Bay of Plenty and Tongariro regions, around the Rotorua, Tokoroa, Taupo triangle, with lesser plantings in the East Cape and Hawkes Bay (Figure 1). Timber produced in the region, mainly *P. radiata* D. Don, generates a large export revenue. There has been a large effort to increase productivity, both by more intensive management and further plantings.

The area is one of high production potential for pines and was historically made available to forestry by the lucky occurrence (for forestry) of a soil cobalt deficiency which manifested itself as "bush sickness" in livestock. This rendered the area unsuitable for pasture production until the cause of the problem was understood and treated (during 1972). Planting of exotic species started at the beginning of this century and continued through to the 1930's. Pressure from agricultural land users and the occurrence of World War II then slowed planting rates until the late 1940's, when a second phase of establishment was undertaken which still continues (Vucetich *et al* 1978). Much of the plantation area is into its second, and sometimes its third, rotation. It is now almost solely composed of *P. radiata* after improved establishment techniques allowed replanting of areas previously suited only to more frost tolerant pines (Hunter *et al* 1986). Furthermore silvicultural operations have increased in intensity over the years. In some areas, planting, which had previously been on cleared native scrub-lands and bush, gave way in the late 1970's and early 1980's to the increased use of improved pasture sites which became available due to a depression in agricultural land prices. This alternative to clearance of native species was attractive both from an economic and ecological point of view.

By the early to mid 1980's the combination of reforesting harvested sites with second or third rotation crops, intensive silvicultural regimes, and the use of old pasture sites for new plantings was normal practice. At the same time nutritional problems involving magnesium, which had first been noticed on a small scale in the 1960's (Will 1961, 1966), became more apparent. Consequently a

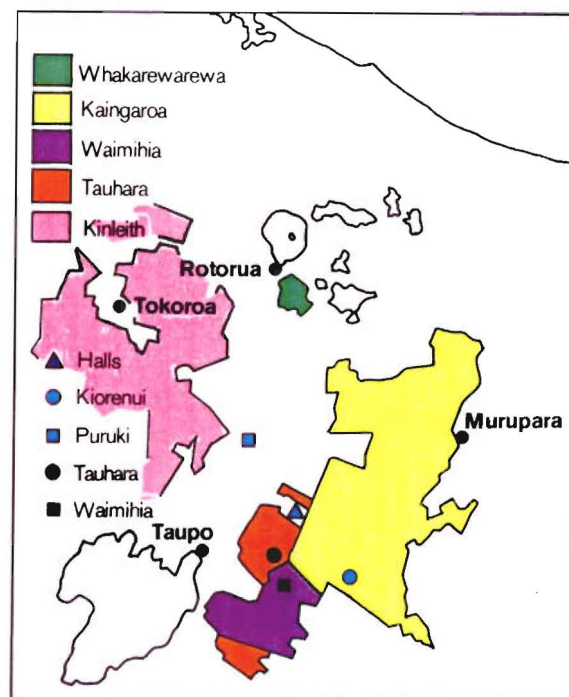


Figure 1. Map of Central North Island Forest locations and trial sites.



research programme was mounted by the New Zealand National Forest Fertilising Cooperative to investigate extent, causes, effects and possible cures for the problem. This study forms part of that programme.

Although pines were planted in the Central North Island from 1900 onwards, magnesium deficiency (Figure 2) was not identified until 1960, when symptoms were noticed in seedlings planted in the Kaingaroa and Whakarewarewa forest nurseries (Will 1961). Three pine species were involved; *P. radiata*, *P. nigra* Arnold and *P. contorta* Dougl., with the former showing the severest symptoms. The needle tips were commonly chlorotic, but in the worst cases the whole needle was chlorotic often with a necrotic tip. The condition was readily treated with an application of magnesium sulphate. Chlorotic trees were also noticed on pumice soils outside the nursery (Will 1966). Slight chlorosis had been noticed in 1- year-old *P. radiata* plantings but more severe chlorosis was found to occur in 3-12 year old stands in Northern Kaingaroa in the vicinity of the Rotorua-Waikaremoana highway. The chlorosis was seasonal, being most marked in spring, and affecting the previous season's needle growth.



Figure 2. Magnesium deficient *P. radiata*.

A summary of work done in 1963 and 1964 (Will 1966) showed that *P. radiata* was the only species affected; the chlorosis was only found in stands established on pumice soils and was confined to trees of 3-15 years of age. Trees older than 15 did not show symptoms. It was suggested that tree roots were able to extract magnesium from buried topsoils by this age. Stands that had been pruned in the previous season showed much more severe chlorosis. The symptoms were generally intensified by other stress factors, such as drought, probably because the major reserves of plant available magnesium occur in the topsoil.

This early phase of the problem was confined to the northern part of Kaingaroa, probably because much of the first rotation plantings in southern Kaingaroa and neighbouring forests was of pine species less sensitive to magnesium stress. However, from 1970 onwards, as the first crop was cleared, improved establishment techniques allowed replanting with *P. radiata* in areas previously unsuited due to frost (Menzies *et al* 1981). No magnesium deficiencies were noticed in the early years, but by 1980 patches of severe chlorosis were noted in 6-year-old stands. The symptoms were generally more severe than those in the northern part of the region with severe chlorosis/needle tip necrosis, stunting of growth, needle shedding and dead lower branches in some stands (Hunter *et al* 1986).

At this time also, widespread incidences of spring chlorosis were beginning to show up in stands planted on old improved pasture sites and these symptoms were severe. Hunter *et al.* (1986) also identified further susceptible sites with a history of topsoil disturbances or which were underlain

by an appreciable depth of water sorted tephra in the profile. It was estimated that 30,000 to 40,000 hectares of *P. radiata* plantations in the central North Island had foliar concentrations on or below the 0.07% Mg critical level as defined by Will (Hunter *et al* 1986).

The dominant cause of the magnesium deficiency is the low magnesium soils underlying the forests. These soils are formed on multiple rhyolitic airfall tephra deposits. They are classified as yellow brown pumice soils (Soil Bureau 1968), they have formed under temperate to cool humid climates and are characterised by the weakly weathered nature of the minerals; this is due to the short period of development of less than 2000 years. The rhyolitic tephra have a low concentration of the elements Al, Fe, Mg, Ca, Ti, Cr, Ni, Co, Ga, Cu and V and soils developed in the tephra are generally of low fertility with high leaching rates and low base status. Cation Exchange Capacity is often low, though it can be much higher where organic topsoils have formed. Other elements required for tree growth such as N, P and K are in good supply in these soils. Where the pumice layers are thin, i.e. at a distance from the eruption centre, buried paleosols developed prior to the eruption and are classified as composite units with the new development. These buried soils are important for forestry.

Since the time the magnesium deficiency was first identified, sporadic research has been undertaken on the problem. The first, in the nursery (Will 1961), was concerned with producing healthy planting stock and results showed quick treatment could be effected with a foliar spray of 2% magnesium sulphate solution, though the effectiveness varied with the time of year the spray was applied. Soil applied  $\text{MgSO}_4$ , at  $250 \text{ kg ha}^{-1}$ , gave a rapid response but the bulk that was not taken up by the plants leached from the profile within a year. Dolomite applied at  $2.5 \text{ tonnes ha}^{-1}$  was found to be better for raising the soil available magnesium levels over a longer period due to its less soluble nature and consequent lower leaching rate. Applications of potassium chloride (KCl), and to a lesser extent ammonium sulphate ( $\text{NH}_4\text{SO}_4$ ) increased the chlorosis of the seedlings. Another low solubility magnesium mineral, serpentine, gave poor results.

By studying seedlings in a pot trial Will (1961) determined foliar critical concentrations to be 0.08-0.11% for magnesium, though this was refined in a later paper to 0.06-0.08% Mg with the advent of Atomic Absorption techniques for measuring magnesium concentrations (Will 1966). Chlorotic trees have normally been found to be within or below this range (Will 1966, Adams 1973, Hunter *et al* 1986).

A preliminary study on young stands of between 3 and 6 years old showed that foliar applications of  $\text{MgSO}_4$  (Epsom salts) in the field reduced chlorosis (Will 1966). However the season chosen for the main study was a wet one and the symptoms previously noted did not occur to the same extent as previous years and may have depressed the potential effect, as no significant improvement was recorded. This served to highlight the importance of soil moisture in magnesium uptake on these sites.

Will and Knight (1968) determined the nutrient supplying potential of six of the common pumice layers occurring in the region. A pot trial using *P. radiata* seedlings showed that of the elements N, P, K, Ca, and Mg, only K and Ca were in adequate supply if all the layers were considered together, although some individual layers were deficient in one or more nutrients. It seemed that magnesium supply would be likely to give future problems, given the low reserve in the soil and amounts likely to be removed by harvesting. However the magnesium supply of some of the buried paleosols was good and if those layers are present at a shallow enough depth to be exploited then the magnesium problem is likely to be lessened when the tree roots reach that layer. The pumice deposits are high in potassium reserves and the relatively high K/Mg ratios could be a potential problem at the root

interface.

Use of nitrogen fertilisers on pumice soils in conjunction with other elements was reviewed by Woollons and Will (1975). They reported that growth in high productivity stands could be improved by application of fertiliser and that N was the only effective element, except for magnesium, which produced a slight response in one trial. The trials reported were 13-14 year old stands however, and they may have been making use of Mg reserves in underlying paleosols by that age. Hunter *et al* (1986) reported similar findings. However they noted that stands established on soils on deep flow tephra (the Waimihia and Matea parts of Kaingaroa) required other nutrients in addition to nitrogen. Stevens (1987), working in Tauhara forest, found that while there were good responses to N, some sites treated did not respond to N and in some cases there was a negative response. He did not consider magnesium but it is possible that N response was lessened by a deficiency in this or another element.

Other recent trials established in southern Kaingaroa (Hunter *et al* 1986, 1991) have studied distribution and fate of applied magnesium fertilisers on unimproved land and also on old improved pasture sites.

On an unimproved site, previously a firebreak, the response to added Mg was slow; foliar levels took two years to increase above the critical concentration when fertilised with a mixture of magnesium sulphate and dolomite at a rate of 100 kg ha<sup>-1</sup> Mg. For the five years following the increased foliage concentration a sustained and strong response of both height and diameter increment was measured. Utilisation of the fertiliser was estimated at 29%. In this trial, plots treated with Mg alone showed characteristic symptoms of boron deficiency at 5 years after application, while those treated with a mixture of magnesium and other fertilisers, including boron, showed no symptoms of deficiency. At another unimproved site in Waimihia, southern Kaingaroa, in a trial established in 1984 an increase in foliar magnesium concentrations was observed but there was no increase in growth rate for three years after fertiliser application (Hunter 1991). Foliar boron concentrations were decreased after dolomite application.

Deficiency symptoms on a pasture site planted with *P. radiata* at Broadlands were more severe than at Waimihia, and in the first year after fertiliser application no increase in foliar magnesium concentration was apparent in the trees. However, foliage concentrations increased after two years and a slight growth increment was measured in plots treated with the more soluble magnesium fertilisers. Pasture dry matter production was not improved, but the pasture magnesium concentrations were increased. An increase of 14-18 kg ha<sup>-1</sup> Mg was measured in the pasture irrespective of rate of fertiliser application (unpublished data, *pers comm.* J.A.C. Hunter 1991).

## STUDY OUTLINE AND OBJECTIVES

When this project was begun in 1988 it was decided to concentrate on the two aspects of the magnesium problem causing most concern and affecting the forests to the greatest extent. The first problem was the seemingly slow response of radiata pine to magnesium fertiliser, and the second the increased severity of the deficiency on sites that had previously been used for pasture production. Other problems such as increased chlorosis on disturbed sites (eg. old firebreaks), sites underlain by water sorted pumice rather than airfall or flow deposits, or greater deficiency caused by pruning of deficient sites were felt to be of lesser importance and so were excluded.



In discussion on these topics a number of possible hypotheses were considered. There were three possibilities why the response to applied fertiliser was slow.

1. It could be a soil problem and related to the solubility or rate of fertiliser application; reaction of the applied magnesium with the soil, or movement of magnesium within the soil profile. Past research (Hunter *et al* 1986, Hunter 1991, Will 1961, Will 1966) had tested various types and rates of magnesium fertiliser, ranging from very soluble magnesium sulphate to less soluble dolomite, magnesium oxide (calcined magnesite), and serpentine. Varying size fractions of the less soluble fertilisers were used. Solubility and rates of dissolution of fertiliser could have contributed to the slow response. The different fertiliser sources will also influence soil pH which can alter the plant available magnesium in the soil. Such changes alter the equilibrium between soil solution magnesium ( $Mg_{ss}$ ) and magnesium adsorbed onto exchange sites in the soil matrix ( $Mg_s$ ). Precipitation reactions are also possible. Here magnesium may become complexed with amorphous aluminium hydroxy groups and form a less readily available compound. Rates of applied fertiliser have ranged up to  $400 \text{ kg ha}^{-1} \text{ Mg}$  for both dolomite and calcined magnesite; but lower rates (up to  $55 \text{ kg ha}^{-1} \text{ Mg}$ ) were tried for serpentine, epsom salts and kieserite. A high rate of  $400 \text{ kg ha}^{-1} \text{ Mg}$  as epsom salts was not tried as it was felt that rapid loss by leaching from the profile would decrease its effectiveness. It was possible that the lower rates of the soluble sources were not high enough to yield a response or that repeated applications would have been required to sustain reasonable Mg levels in the soil.
2. It could be a tree problem. Thus a slow response might be due to the degree of deficiency or age of the tree, rooting pattern and intensity, the uptake capacity of the roots, an imbalance with other nutrients, or even a deficiency of a nutrient other than Mg. Magnesium plays an important role in photosynthesis in the tree and also in the transformations of photosynthate. A deficiency may therefore cause differences in the pattern of allocation of carbon to the root system, affecting both rooting intensity and possibly mycorrhizal activity (Marschner 1986). This effect could in turn be coupled to the magnesium uptake rates of the root. It is thus possible a tree might not be able increase Mg uptake associated with increased supply of Mg from fertiliser without first generating more roots. Ionic imbalances with both  $K^+$  and  $NH_4^+$  are known to affect magnesium uptake by plants (Barber 1984), and the pumice soils have high levels of available potassium. Antagonism between  $Mn^{2+}$  and  $Mg^{2+}$  has also been recorded in radiata pine.
3. There are two likely contributors to the deficiency problem on ex pasture sites. The first involves the fertiliser history of the sites. A long record of fertilisation with superphosphate, potassium chloride and lime may have led to an increased leaching loss of magnesium from the profile following exchange of applied cations with adsorbed magnesium. However, it is likely that to avoid hypomagnesaemia in stock, additions of magnesium may have been made on these soil types. The second more likely explanation, is competition between the trees and grass on the site for water and/or magnesium, thus limiting uptake by the trees.

To address these soil chemical, physiological and environmental topics I designed two field experiments; one on a newly planted pasture site in Tauhara forest (Halls Block) and the other in a mature stand in southern Kaingaroa forest (at Kiorenui). These were supplemented by a number of glasshouse studies; plus laboratory based soil chemical investigations. The aim of the research programme was to gain a fuller understanding of magnesium nutrition of radiata pine planted on pumice soils and to explain the slow response to fertiliser and the poorer nutrition on ex-pasture sites.



Central to these investigations was the to model magnesium uptake by radiata pine.

The structure of the research programme is shown in Figure 3, with the proposed output. Eight specific objectives of the programme were identified.

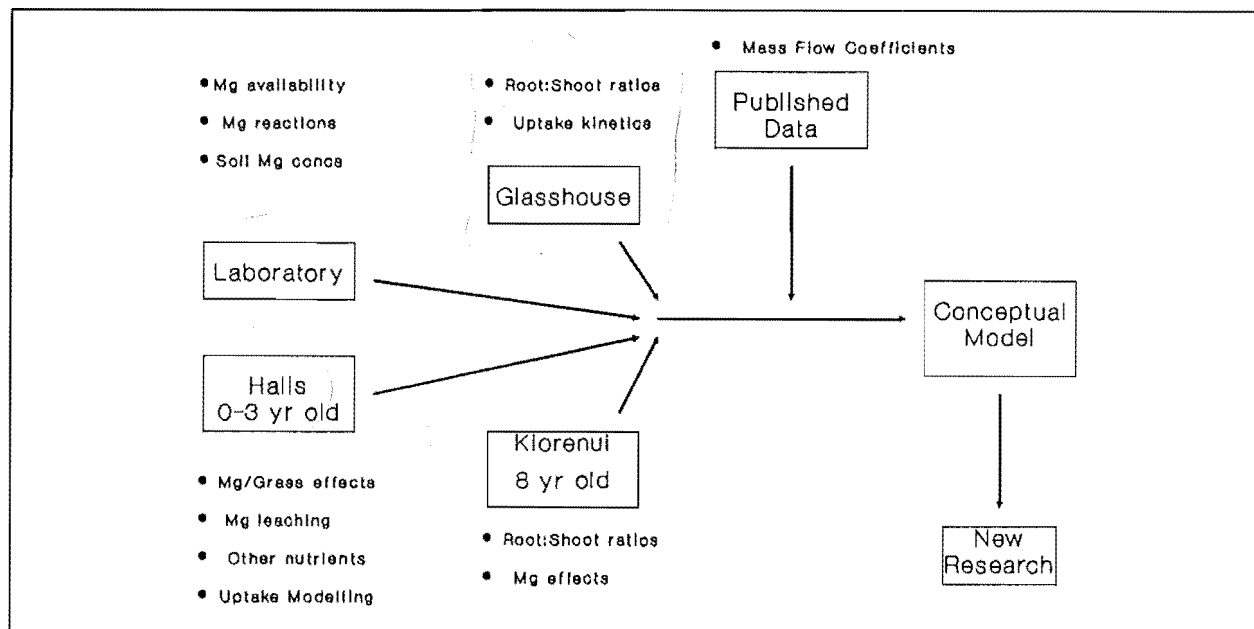


Figure 3. Research programme structure.

Objective 1: To determine the reactions of magnesium applied to pumice soils.

This work was laboratory based and utilised soil from the Halls trial site plus soil from two other Forestry Research Institute magnesium trials in the locality. The soil chemical reactions of the three commonly used fertilisers; calcined magnesite, dolomite and epsom salts were investigated. The various soil magnesium fractions (solution, exchangeable, reserve and total) were measured and the distribution of Mg in the soil and availability to the tree assessed.

Objective 2: To determine residence time of fertiliser Mg in the soil profile.

This field study was based at the Halls trial site and covered distribution of applied fertiliser within the profile with time, and also the chemical reactions of applied Mg with the soil in a field situation. A soluble and insoluble fertiliser source were used and the effect of grass cover assessed.

Objective 3: To determine how quickly magnesium can be assimilated by young and old trees when fertiliser is applied.

Improvement of foliar Mg ( $Mg_f$ ) concentrations has been shown to be slow in previous studies (Hunter 1991). This may have been due to rate or solubility of fertiliser source. Therefore two experiments, one at Halls in a juvenile stand, and one in mature deficient trees at Kiorenui were designed. The aim

was to test the effect of soluble Mg as epsom salts at  $400 \text{ kg ha}^{-1}$  Mg on foliar Mg concentrations and growth. If rapid improvement occurred (i.e. an increase in Mg, in less than 6 months) then it would suggest the slow response had previously been due to solubility and/or rate of applied fertiliser. If the Mg<sub>f</sub> concentrations did not rise this would suggest a physiological problem in the tree. At the Halls site calcined magnesite was also evaluated, at  $400 \text{ kg ha}^{-1}$  Mg.

Objective 4:        *To assess the impact of grass competition on tree growth and Mg uptake.*

The site at Halls was used to test the effect of grass and Mg fertilisers in combination on Mg uptake and tree growth. Soil moisture conditions were monitored on grassed and ungrassed treatments.

Objective 5:        *To determine what effect Mg deficiency has on tree growth and carbon allocation.*

The two sites at Halls and Kiorenu were utilised for this investigation. A full biomass study at the Halls site, plus root assay in deficient and non deficient stands at Kiorenu were planned to investigate the C allocation patterns. In addition work in the glasshouse with perlite medium at different magnesium solution concentrations was planned to gain information over a range of deficiency levels.

Objective 6:        *To determine what effect other nutrients have on magnesium nutrition of radiata pine.*

Boron and magnesium deficiencies often occur on the same sites and it may be that some interaction of these two elements affects response to applied magnesium. This was investigated at the Halls site as both Mg and B deficiency occur in the vicinity. In addition a total spectrum fertiliser was used to determine if any other element not previously implicated could be affecting magnesium nutrition.

Objective 7:        *To fit findings into a nutrient uptake model to aid overall understanding of the system.*

The data gathered on nutrient uptake, soil chemistry, climate and soil moisture from the Halls trial were used in Barber's (1984) nutrient uptake model. To employ this model additional information on nutrient uptake kinetics of *P. radiata* were obtained from glasshouse experiments using solution culture techniques. Other required information was obtained from literature sources. Sensitivity analyses were used to highlight the important factors affecting the uptake of Mg by *P. radiata*.

Objective 8:        *To evaluate the research programme and assess the implications for managing the Mg nutrition of P. radiata on pumice soils.*

This objective was reached by synthesising the information gathered by this research programme plus other information available in the literature. Findings were summarised as a set of rules which were the basis of an expert system.

## Chapter 2

### Reaction of dolomite, calcined magnesite and Epsom salts with yellow brown pumice soils

#### INTRODUCTION

*Pinus radiata* planted on pumice soils in New Zealand often exhibits symptoms of magnesium deficiency, and an estimated 30,000 to 40,000 hectares of plantation have foliar concentrations on or below the critical value of 0.07% Mg (Hunter *et al.* 1986). The deficiency is most common on the southern end of the Kaingaroa plateau and is generally more severe on sites which were previously used for pasture production or where the topsoil has been removed or heavily disturbed.

The soils underlying the plantations are classed as Yellow-Brown Pumice (YBP) soils (NZ Soil Bureau 1968). These are young poorly weathered soils of less than 2000 years with a low cation exchange capacity and base status. The clay content, which is predominantly allophane, is low. Total magnesium concentrations in these soils are normally less than 0.5%, and of this less than 5% is in a plant available form (Metson and Brooks 1975). Of the plant available fraction, three components can be identified; soil solution magnesium ( $Mg_{ss}$ ), exchangeable magnesium ( $Mg_e$ ), and reserve or acid soluble magnesium ( $Mg_r$ ). Levels of the latter two components are low compared to other New Zealand soils (Blakemore *et al.* 1981).

A horizon  $Mg_e$  concentrations average about  $1.0 \text{ meq}100\text{g}^{-1}$ , and B horizon concentrations are normally less than  $0.5 \text{ meq}100\text{g}^{-1}$  (Metson and Brooks 1975, Metson and Gibson 1977, Gibbs 1980). Mean  $Mg_r$  concentrations are  $2.8 \text{ meq}100\text{g}^{-1}$  in the topsoil and  $2.1 \text{ meq}100\text{g}^{-1}$  in the subsoil (Metson and Brooks 1975). Very few data are available for  $Mg_{ss}$  concentrations; Hunter (1991) recorded levels of  $0.24 \text{ mgL}^{-1}$  Mg on a severely deficient site into southern Kaingaroa; Mg concentrations in streams flowing from the Puruki experimental catchment in southern Kaingaroa ranged from 0.3 to  $0.5 \text{ mgL}^{-1}$  (P. Hodgkiss *pers comm.* 1991). These are very low in comparison to soil solution magnesium concentrations summarised by Barber (1984) for agricultural soils, where mean values were in the order of  $50 \text{ mgL}^{-1}$ . In areas of forest decline in Germany associated with Mg deficiency, concentrations were of the same magnitude as those found by Hunter (Meyer *et al.* 1988).

It seems therefore that these soils are deficient in plant available magnesium. The problem, however, is to try and determine what levels are adequate for growth of *P. radiata*. Adams (1973) found no correlation between severity of deficiency in *P. radiata* and exchangeable Mg ( $Mg_e$ ) concentrations, but did propose a soil critical value of 500 to  $600 \text{ mgkg}^{-1}$  ( $4.11$  to  $4.93 \text{ meq}100\text{g}^{-1}$ ) for acid extractable Mg ( $Mg_r$ ), below which a deficiency could be expected. Neither Hunter (1991) or Ballard *et al.* (1971) found a relationship between  $Mg_e$  and foliar magnesium ( $Mg_f$ ) concentrations in radiata pine with studies which covered the whole of New Zealand. Will (1960) working with solution cultures found that a solution concentration of at least  $10 \text{ mgL}^{-1}$  Mg was required to maintain good growth in *P. radiata*. Attempts to alleviate the magnesium stress and improve the magnesium status and growth of deficient trees has met with mixed response, but generally foliar Mg concentrations are slow to increase, and growth responses only occur after 3 to 5 years (Hunter *et al.* 1986). As a variety of different sources, rates and grades of magnesium fertiliser have been tried, an understanding of

how fertilisers affect the soil magnesium levels was required to explain this slow response. There are two possible causes. First, the sources of Mg previously used have only been slowly available due to low solubility, or secondly that the applied magnesium has been rapidly tied up in an unavailable form - something akin to a phosphate fixation problem. The soil clay fraction is dominated by allophane, which has a pH dependent charge. Varying the soil pH could affect the availability of magnesium, by changing the proportion of Mg adsorbed on the exchange complex to that in solution (Sumner *et al* 1991). Magnesium fertiliser types that both raise (dolomite) and lower (Epsom salts) soil pH have been used, and this could be a confounding factor in subsequent plant availability. Furthermore an increase of soil pH has been shown to decrease exchangeable Mg levels in such soils through the formation of less soluble magnesium aluminium hydroxy compounds (Grove *et al* 1981). If this occurred it could help explain the slow response of the trees to applied Mg. However, if plant available Mg was rapidly increased by applied Mg, then the problem may be linked to the tree's ability to assimilate magnesium.

## OBJECTIVE

To determine the distribution of Mg in various forms in pumice soils, to determine the effect of 1) varying soil pH, and 2) adding magnesium fertilisers on the concentrations and distributions of the various forms of magnesium in the soil.

In order to investigate the soil chemistry of these pumice soils, samples of soil from three field trial sites were used to study the effect of applying the three magnesium fertilisers most commonly used in previous experiments (Epsom salts, dolomite and calcined magnesite) on the solution, exchangeable and reserve fractions of magnesium.

## MATERIALS AND METHODS

### Soil Sampling

Soils from three forest fertiliser trial sites established on pumice soils near Taupo New Zealand were used in this study. The trials had a range of magnesium fertiliser histories;

1. The Waimihia site had been planted directly from reclaimed scrubland (Hunter 1991);
2. The Tauhara site was originally improved pasture 15 years prior to soil sampling (Hunter 1991);
3. The Halls site was existing pasture with newly planted trees.

Composite A<sub>1</sub> horizon core samples were taken from the control plots of each trial. Samples were air dried and sieved to <2mm prior to use in the experiments.

### Experimental

1. Effect of pH on Mg availability: To study the effects of pH changes on Mg availability, buffer curves were constructed for the three soils by equilibration with varying volumes of 0.022M Ca(OH)<sub>2</sub> and H<sub>2</sub>SO<sub>4</sub> (Lincoln University Dept Soil Science 1990). The amount of acid or base

required to change the soils' pH by -1.0, -0.5, 0, +0.5, and +1.0 units was calculated for each soil. The required amount of acid or base was added to 120g subsamples of the soils and equilibrated at 20°C and at field moisture capacity for thirty days. The design was fully randomised with two replicates. The water added contained 1% chloroform to inhibit microbial activity. Soil pH changes have been found in equilibration studies where such activity is not inhibited (Haynes and Swift 1989).

2. Effect of fertilisers on Mg availability: A second study varied application rates of Epsom salts ( $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ ), dolomite ( $\text{CaCO}_3 \cdot \text{MgCO}_3$ ), and calcined magnesite ( $\text{MgO}$ ). The experiment was a  $3 \times 3 \times 4$  factorial with two replicates in a fully randomised design. Each of the three soils had the three types of fertiliser applied at 0, 100, 200 and 400  $\text{kg ha}^{-1}$  Mg. The fertiliser was added to between 120 and 200 gram subsamples of the soil. Both the dolomite and calcined magnesite were added as a 68 micron powder and thoroughly mixed, the Epsom salts was added as a solution. Equilibration conditions were the same as for the acid/base experiment.

## Chemical Analysis

Following the equilibrations with the various treatments the magnesium content of the soils was fractionated into soil solution Mg ( $\text{Mg}_{\text{ss}}$ ), exchangeable Mg ( $\text{Mg}_{\text{e}}$ ), acid extractable or reserve Mg ( $\text{Mg}_{\text{a}}$ ) and total Mg ( $\text{Mg}_{\text{t}}$ ).

- \* Soil Solution Mg: Soil solution was extracted by the method of Elkhatib *et al.* (1987). The soil at field capacity was packed into 100ml centrifuge tubes. The tubes had a single hole at the bottom with a disk of filter paper placed over it prior to filling. These tubes were placed inside larger tubes and centrifuged at 4000rpm (approximately equivalent to 15 bar suction (M. Davis and P. Clinton *pers comm.* 1988)) until sufficient solution for chemical analysis had been extracted. The solution was stored sealed at below 5°C. Solution pH and base cation concentrations were determined. Cation concentration was measured by atomic absorption spectroscopy, and results expressed as  $\text{mg L}^{-1}$ .
- \* Exchangeable Mg, Other Cations, and Cation Exchange Capacity: Ten gram samples of moist soil were rapidly leached with 20ml of 95% ethanol to remove the entrained soil solution and then leached overnight with neutral 1N ammonium acetate to extract the exchangeable base cations (Nicholson 1984). Acid cations (Al and Mn) were extracted similarly but using 1N KCl as the extractant (Nicholson 1984). All cations (Ca, Mg, K, Na, Al, & Mn) were analyzed by atomic absorption spectroscopy using  $\text{LaCl}_2$  as an ionisation suppressant (Nicholson 1984). Results were expressed as  $\text{meq } 100\text{g}^{-1}$  (equivalent to  $\text{cmol} \cdot \text{kg}^{-1}$  in SI units). The proportion of exchangeable Mg on the cation exchange sites was expressed as a percentage of the total exchange capacity. The cation exchange character of the soil was described as in Edmeades and Judd (1980) as the effective cation exchange capacity (ECEC). It is the sum of the base cations and KCl extractable Al and Mn. All results were expressed on an oven dried weight basis, following determination of moisture content by drying sub samples of soil to constant weight at 105°C.
- \* Available Mg: Available Mg ( $\text{Mg}_{\text{av}}$ ) was calculated from the sum of  $\text{Mg}_{\text{ss}}$  and  $\text{Mg}_{\text{e}}$ , expressed as  $\text{meq } 100\text{g}^{-1}$ , calculated by converting the  $\text{Mg}_{\text{ss}}$  to  $\text{meq } 100\text{g}^{-1}$  using the volumetric water content at field capacity for each soil and the solution Mg concentrations.

- \* Acid extractable Mg: Acid extractable Mg (Mg<sub>a</sub>) was measured by extraction of Mg from 1 gram samples of air dried soil in boiling 1N HCl for 15 minutes (Adams 1973). The result was expressed on an oven dry basis as actual Mg<sub>a</sub> by correcting for Mg<sub>e</sub> and Mg<sub>ss</sub> content.
- \* Total Mg: Total magnesium was analyzed on the control samples. X-ray fluorescence on a fused pellet was the method used (S. Wright *pers comm* 1989).
- \* Soil pH: Soil pH was measured on air dried soil samples using a soil:solution ratio of 1:2.5 (Nicholson 1984).

## Statistics

The acid/base equilibration was analyzed as a fully randomised design consisting of five treatments with two replicates. The fertiliser equilibration was analyzed as a 3\*3\*4 factorial with two replicates. Analysis of variance and regression procedures were used within the SAS statistical software package (SAS Institute 1985).

## RESULTS

### Effect of Changing pH on Magnesium Availability

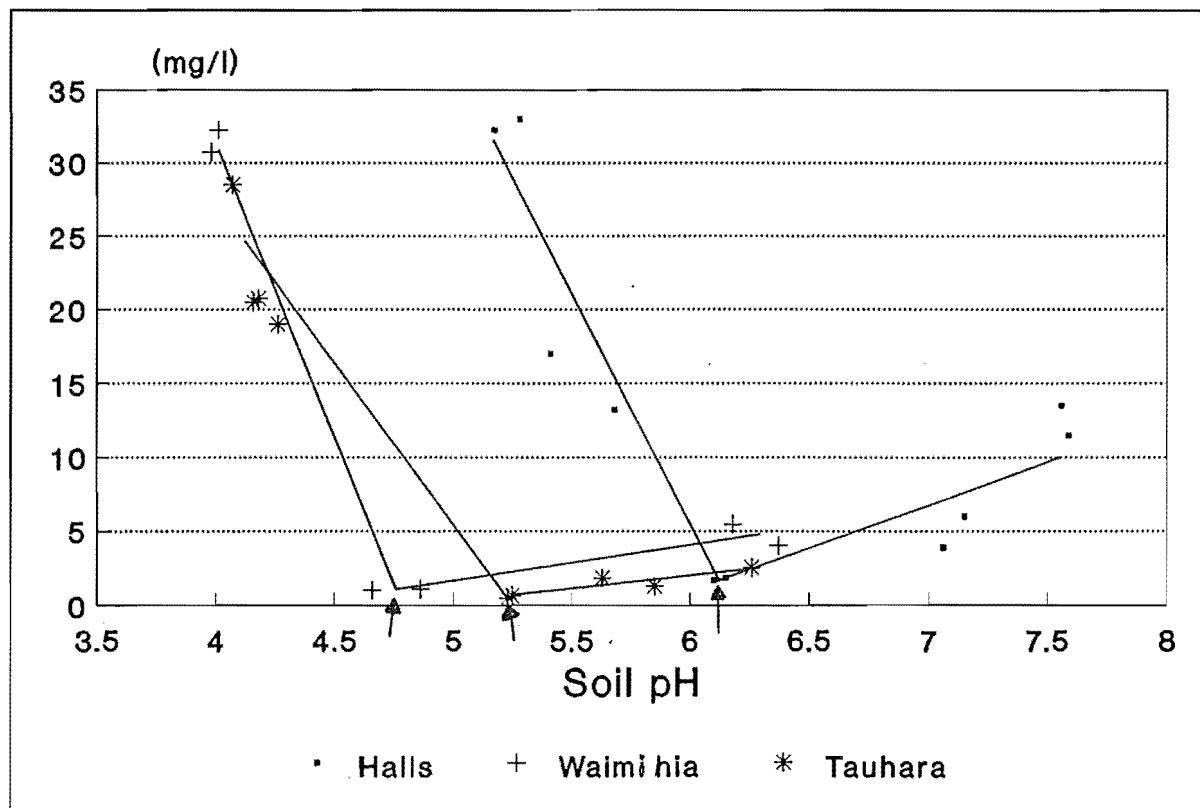


Figure 1. Effect of varying soil pH on soil solution Mg concentrations. Field pH is indicated by arrows on the plots.

Changing soil pH caused a change in  $Mg_{ss}$  concentrations, and this differed by site and treatment (Table 1), though the shapes of the curves were similar (Figure 1).  $Mg_{ss}$  concentrations increased when pH was either increased or decreased for all three soils. A greater increase was apparent when the soils were acidified than when their pH was raised. This may be explained by the release of acid soluble forms of Mg onto exchange sites and into solution in addition to the exchange of  $H^+$  in solution with  $Mg^{2+}$  ions adsorbed onto exchange sites. The increase in  $Mg_{ss}$  as pH is increased is likely to be solely due to ion exchange reactions. The magnitude of the increase in  $Mg_{ss}$  concentration with acidification is similar for the Halls and Tauhara soils but is largest for the Waimihia soil. Unfortunately the -1.0 pH unit treatment was not done for the Waimihia site, as the treatment added was inadvertently a -0.5pH unit change instead of -1.0 unit change. But a concentration in the order of  $60\text{ mgL}^{-1}$  might be expected compared to 20 and  $30\text{ mgL}^{-1}$  for the Tauhara and Halls soils.

**Table 1.** Effect of changing soil pH on soln Mg ( $\text{mgL}^{-1}$ ), exchangeable and available Mg ( $\text{meq100g}^{-1}$ ), and buffer power. ANOVA probability levels and standard errors.

Site	Treatment		Trait			
	delta pH	$Mg_{ss}$	$Mg_e$	$Mg_{av}$	ECEC	Buffer
Halls	-1.0	32.6	0.89	1.27	22.01	3.3
	-0.5	15.1	0.92	1.13	20.82	8.5
	0.0	1.7	0.89	0.92	20.11	61.5
	+0.5	4.9	0.59	0.67	28.12	16.8
	+1.0	12.5	0.86	1.03	15.79	8.5
Waimihia	-1.0	nd	nd	nd	nd	nd
	-0.5	31.5	0.30	0.95	12.60	1.1
	0.0	1.0	0.40	0.42	9.81	48.8
	+0.5	1.8	0.47	0.49	18.08	30.4
	+1.0	4.7	0.12	0.22	11.26	3.3
Tauhara	-1.0	20.6	0.30	0.70	4.66	1.8
	-0.5	23.7	0.34	0.65	5.72	2.2
	0.0	0.6	0.42	0.43	6.10	90.8
	+0.5	1.5	0.40	0.43	9.59	32.2
	+1.0	2.5	0.36	0.39	12.40	17.8
Source of variation		Probability > F				
Treatment		0.0001	0.0021	0.0001	0.0001	0.0001
Site		0.0080	0.0001	0.0001	0.0001	0.0208
Tmt*Site		0.0001	0.0043	0.0001	0.0001	0.0397
Std Error		1.567	0.0283	0.0225	0.6698	4.506

Usually  $Mg_e$  concentrations decrease from low to high pH - see for example Grove *et al* (1988) and Edmeades *et al* (1985). However this did not occur in this study. The  $Mg_e$  values decreased with both increasing or decreasing pH (Figure 2) in the Waimihia and Tauhara soils. The Halls soil showed no differences in  $Mg_e$  with change in pH.

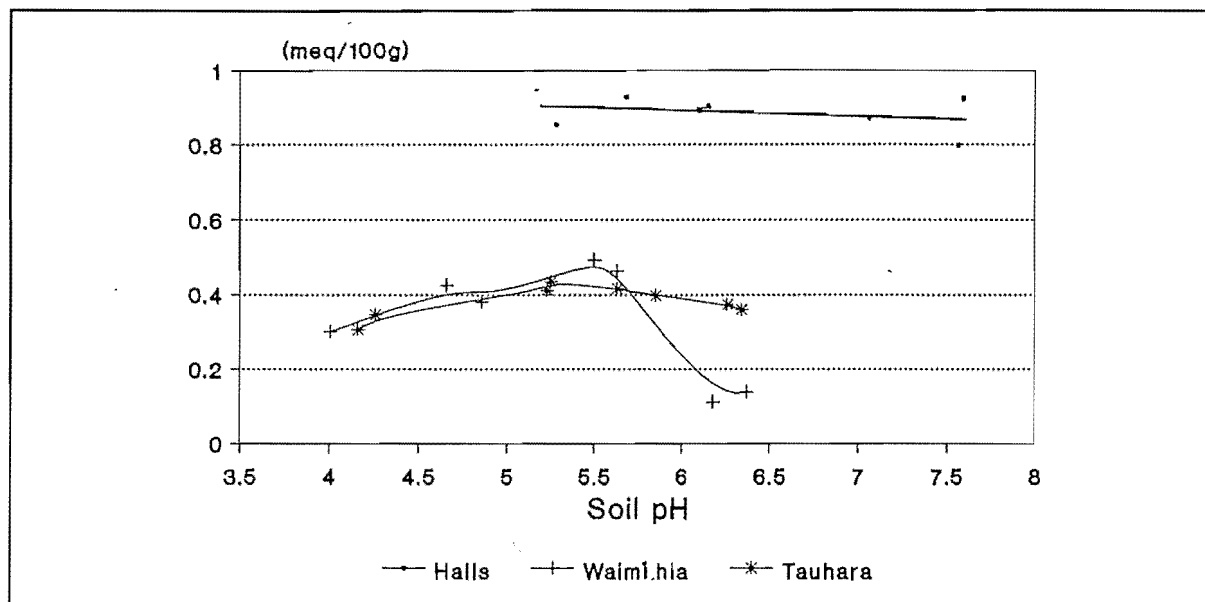


Figure 2. Relation between pH and  $Mg_e$ .

To show a clearer picture, in which trends in available Mg are not obscured by differences in distribution between solution and exchange phase caused by the treatments, the available Mg ( $Mg_{av}$ ) or sum of solution and exchange concentrations were calculated (Table 1). Regression of this variable against soil pH showed a decrease in magnesium availability with increasing pH for the Waimihia and Tauhara soils but no significant effect for the Halls soil (Table 2, Figure 3). The strongest effect was shown by the Waimihia soil, where changing the pH by 1 unit changed the  $Mg_{av}$  by  $0.24 \text{ meq}100\text{g}^{-1}$ .

Table 2. Regressions for predicting change in available Mg ( $Mg_{av}$ ) with change in pH for soils from the Halls, Waimihia, and Tauhara sites.

Site	Regression Equation	$r^2$	$P > F$
Halls	$Mg_{av} = 1.66 - 0.0946 \text{ pH}$	0.3756	0.1062
Waimihia	$Mg_{av} = 1.74 - 0.2419 \text{ pH}$	0.6982	0.0192
Tauhara	$Mg_{av} = 1.22 - 0.1376 \text{ pH}$	0.8475	0.0012

It is apparent that alteration of pH affected both availability of Mg and also the equilibrium between the solution and exchange phase. This equilibrium can be expressed as the buffer power (b), or ratio of exchangeable:solution Mg expressed on a volumetric basis. Buffer power was decreased quite substantially by treatments, irrespective of the direction of pH change, but was related to magnitude of change in soil solution concentration (Table 1). This change has implications both



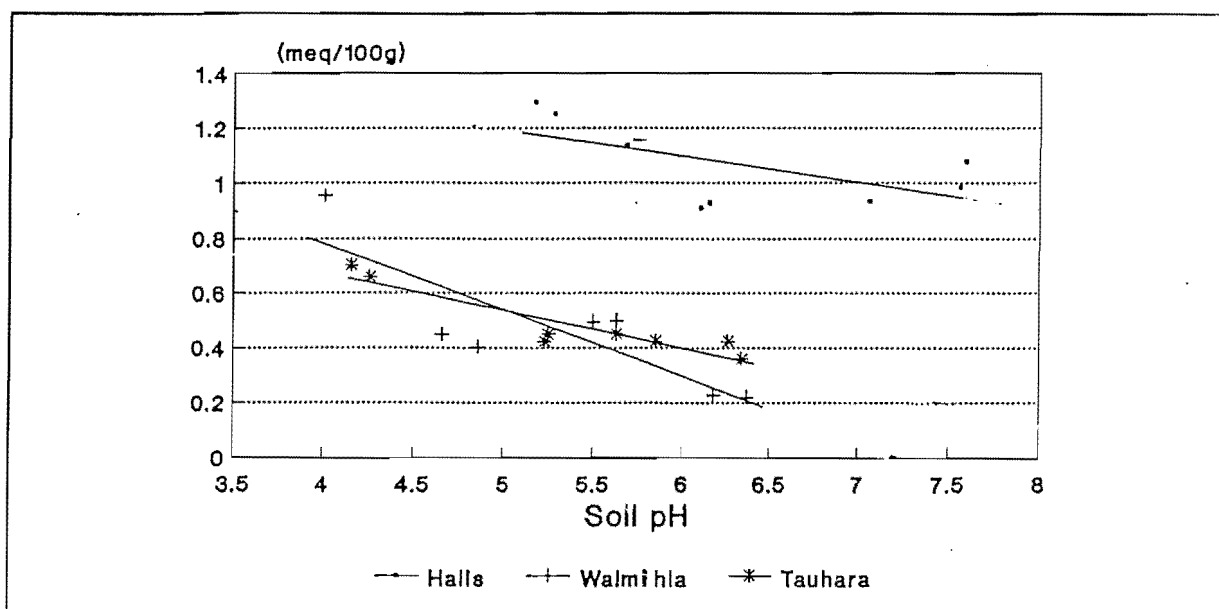


Figure 3. Relation between pH and labile Mg ( $Mg_{av}$ ) for the three soils.

for plant nutrient supply and also for leaching losses of Mg from the soil profile. The release of Mg into solution increases the potential leaching losses of Mg from the profile, and if the change in buffer power is maintained the long term Mg supply could be decreased if Mg losses by leaching are substantial.

#### Effect of Changing Soil pH on Charge Characteristics

Modifying soil pH can cause a change in exchange capacity (ECEC) and this can buffer the soil against leaching loss when fertilisers are applied (Edmeades and Judd 1980). The ECEC of the three soils ranged from 6.1 meq100g<sup>-1</sup> at Tauhara to 20.1 meq100g<sup>-1</sup> at Halls. Changing the pH only significantly affected the ECEC at Tauhara ( $P=0.0011$ ) where it increased from 4.66 meq100g<sup>-1</sup> at pH 4.20 to 12.40 meq100g<sup>-1</sup> at pH 6.34 (Table 1).

#### Effects of Rates of Mg on Soil Mg and Other Cations

Soil solution Mg increased in concentration with increasing rate of fertiliser, from a mean value of 1.6 mgL<sup>-1</sup> in the control to 37.6 mgL<sup>-1</sup> at 400 kg ha<sup>-1</sup> (Table 3). Increasing the amount of Mg applied to the soil caused a linear increase in exchangeable Mg, from 0.72 meq100g<sup>-1</sup> in the control, to 3.16 meq100g<sup>-1</sup> in the 400 kg ha<sup>-1</sup> treatment. These changes in solution and exchangeable levels did not alter buffer power significantly, though the values did trend downwards with increase in applied Mg. The percentage Mg on the exchange sites also increased; from 9.1% in the control to 27.7% at the highest rate of application. There was an increase in reserve Mg concentration with increasing rate of fertiliser. Concentration in the control was 0.65 meq100g<sup>-1</sup> and 1.36 meq100g<sup>-1</sup> in the 400 kg ha<sup>-1</sup> treatment (Table 3).

**Table 3.** The effect of rate of magnesium fertiliser on concentrations of soil Mg fractions and buffer power<sup>1</sup>. Probabilities of rate differences (from ANOVA) and standard errors.

Rate	Mg <sub>ss</sub>	Mg <sub>e</sub>	Mg <sub>av</sub>	Mg <sub>r</sub>	% Mg	Buffer
kg ha <sup>-1</sup>	mg l <sup>-1</sup>	meq 100g <sup>-1</sup>				
0	1.6	0.72	0.72	0.65	9.1	63.2
100	7.6	1.44	1.50	0.83	16.8	57.0
200	18.7	2.12	2.27	1.08	20.4	41.24
400	37.6	3.16	3.39	1.36	27.7	41.53
Source of variation                      Probability > F						
Treatment	0.0001	0.0001	0.0001	0.0005	0.0001	0.1453
Std Error	0.006	0.032	0.033	0.108	0.426	7.99

<sup>1</sup> Data combined from all sites and fertiliser types. %Mg is percentage Mg on exchange sites, Buffer is the ratio of Mg<sub>e</sub>:Mg<sub>ss</sub>.

Total magnesium concentrations were 22.05 meq 100g<sup>-1</sup> at Halls, 30.94 meq 100g<sup>-1</sup> at Waimihia and 23.37 meq 100g<sup>-1</sup> at Tauhara. Analysis of the other cation concentrations (Ca, K, Na, Al, Mn) showed the added Mg to be displacing predominantly Al from the exchange sites, this element's concentration decreasing, while K and Na were not significantly affected and Ca actually increased slightly (Table 4). This was probably due to the influence of the Ca content in the dolomite on the overall analysis. As a consequence of adding magnesium the Ca:Mg ratio was improved from 5.45 in the control to 1.29 in the maximum treatment (400 Kg ha<sup>-1</sup> Mg).

**Table 4.** The effect of rates of magnesium fertiliser on soil cations and exchange capacity. Data combined from all sites and fertiliser types.

Rate	Ca	K	Na	Al	Mn	ECEC
kg ha <sup>-1</sup>	meq 100g <sup>-1</sup>					
0	3.38	0.37	1.64	2.88	2.17	11.02
100	3.26	0.46	1.33	2.31	1.86	10.68
200	3.78	0.33	1.51	1.99	2.18	11.94
400	4.10	0.32	2.02	1.62	2.07	13.31
Source of variation                      Probability > F						
Treatment	0.0001	0.2456	0.2951	0.0001	0.5271	0.0009
Std Error	0.074	0.066	0.212	0.144	0.092	0.305

The amount of magnesium fixed in a form unavailable to the plant or released from unavailable fractions was calculated by comparing the measured  $Mg_{av}$  concentration after reaction with the fertilisers, with the theoretical concentration based on the soils' initial concentration and the amount of Mg added in each treatment (Table 5). A positive figure signified an overall fixation by the soil, a negative value a release of Mg into the available form. Analysis of variance showed rate, type of fertiliser and site were all highly significant in affecting the difference ( $P=0.0001$ ), as were the interactions of the factors. In general there was a higher concentration of  $Mg_{av}$  after treatment than the theoretical maximum and this release of Mg increased with rate of applied Mg. It varied with the type of fertiliser. The Halls soil when treated with dolomite, showed a fixation of Mg of between 0.176 and 0.424 meq100g<sup>-1</sup>. Fixation was also recorded in three instances where calcined magnesite was used. In no cases did soils show fixation after treatment with  $MgSO_4$ . Soils treated with  $MgSO_4$  showed a greater release than the other two sources of Mg (Table 5). The two factors likely to cause this release are; pH changes to the soil or soil solution, and the ionic strength of the soil solution. At the maximum Mg application rate  $MgSO_4$  lowered soil pH by an average of 0.51 units in the three soils, while dolomite raised pH by 0.32 units and calcined magnesite caused a smaller increase of 0.14 units.

**Table 5.** Deviation of measured available Mg ( $Mg_{av}$ ) concentrations from the theoretical value following reaction with calcined magnesite, dolomite and Epsom salts.

Site	Rate kg ha <sup>-1</sup>	Difference (meq100g <sup>-1</sup> )		
		Type		
		C'Mag	Dolomite	MgSO <sub>4</sub>
Halls	0	-0.014	-0.014	-0.014
	100	0.236	0.176	-0.344
	200	-0.192	0.317	-1.207
	400	-0.190	0.424	-1.297
Waimihia	0	-0.023	-0.023	-0.023
	100	-0.890	-0.443	-0.441
	200	0.259	-0.879	-0.801
	400	-0.667	-1.183	-0.494
Tauhara	0	-0.007	-0.007	-0.007
	100	-0.208	-0.428	-0.455
	200	-0.260	-0.805	-0.909
	400	0.121	-0.786	-1.039

The various sources of Mg changed ionic strength differently (calculated from soil solution conductivity using the method of Black and Campbell 1982).  $\text{MgSO}_4$  caused the greatest increase while dolomite and calcined magnesite had a much smaller effect. It was possible to model these changes using multiple regression. The best model, using data from all treatment combinations (Equation 1) contained ionic strength and soil solution pH and explained 71% of the variation.

$$\text{Difference from theoretical change in } \text{Mg}_{\text{av}} = -1.011 + 0.1733(\text{pH}_{\text{ss}}) - 0.056(\text{IS}) \quad (1)$$

$$r^2 = 0.7090 \quad P > F = 0.0001$$

Ionic strength was the most significant component of the model ( $P=0.0001$ ) while  $\text{pH}_{\text{ss}}$  contributed less ( $P=0.1085$ ). This suggests that a combination of pH change and overall solution concentration explains the release or fixation of Mg by the soils.

Finally, the effect of the rates of fertiliser on soil ECEC was assessed. The maximum rate of  $400\text{kg ha}^{-1}$  caused a mean increase in ECEC of  $2.18\text{ meq } 100\text{g}^{-1}$  over the control ( $P=0.0001$ ).

### Effects of Types of Fertiliser on Soil Mg and Other Cations

The overall ANOVA showed that the type of fertiliser generally had less of an effect on soil Mg and other variables than rate of fertiliser added. There was a strong difference in mean  $\text{Mg}_{\text{ss}}$  values between types;  $\text{MgSO}_4$  had a mean concentration of  $40\text{ mg L}^{-1}$  while the dolomite and calcined magnesite means were 4 to  $5\text{ mg L}^{-1}$  (Table 6). The mean values for  $\text{Mg}_{\text{e}}$  showed the value for calcined magnesite to be lower than both dolomite and  $\text{MgSO}_4$  at  $1.72\text{ meq } 100\text{g}^{-1}$  vs 1.90 and  $1.96\text{ meq } 100\text{g}^{-1}$  respectively. There was a strong effect of type of magnesium source on buffer power ( $P=0.0001$ ) with  $\text{MgSO}_4$  treated soils having a much smaller buffer power at 6.7 than calcined magnesite and dolomite at 48.9 and 50.8. However there was no effect of type on reserve Mg ( $\text{Mg}_{\text{r}}$ ) concentrations or percentage Mg on the exchange complex.

**Table 6.** Effect of type of Mg fertiliser on soil Mg fractions and buffer power<sup>1</sup>. Data combined across sites and rates.

Type	$\text{Mg}_{\text{ss}}$	$\text{Mg}_{\text{e}}$	$\text{Mg}_{\text{av}}$	$\text{Mg}_{\text{r}}$	% Mg	Buffer
	$\text{mg L}^{-1}$	$\text{meq } 100\text{g}^{-1}$				
C'Mag	4.6	1.72	1.75	0.93	18.25	48.99
Dolomite	4.3	1.90	1.94	1.08	18.57	50.84
$\text{MgSO}_4$	40.4	1.96	2.22	0.85	18.76	6.74
Source of variation      Probability > F						
Type	0.0001	0.0001	0.0001	0.2217	0.6248	0.0001
Std Error	0.109	0.027	0.029	0.094	0.370	7.24

<sup>1</sup>. %Mg is percentage Mg on exchange sites, buffer is ratio of  $\text{Mg}_{\text{e}}:\text{Mg}_{\text{ss}}$ .

Of the other cations, dolomite raised the  $\text{Ca}_e$  concentration compared to both the calcined magnesite and the  $\text{MgSO}_4$  (Table 7). This was due to the calcium content of the dolomite. The Al concentration was also affected by type of fertiliser, with dolomite lowering the exchangeable Al concentration. The ECEC was also altered by type of fertiliser, with  $\text{MgSO}_4$  causing the highest and calcined magnesite the lowest levels.

**Table 7.** Effect of type of Mg fertiliser on exchangeable cations and ECEC. Data combined across sites and rates.

Type	Ca	K	Na	Al	Mn	ECEC
	meq100g <sup>-1</sup>					
C'Mag	3.23	0.45	1.42	2.14	1.99	10.93
Dolomite	4.39	0.33	1.62	1.45	2.11	11.79
MgSO <sub>4</sub>	3.28	0.33	1.84	3.01	2.10	12.49
Source of variation                      Probability > F						
Type	0.0001	0.2456	0.2951	0.0001	0.5271	0.0009
Std Error	0.065	0.057	0.184	0.125	0.079	0.264

These results were reflected in the difference to expected theoretical  $\text{Mg}_{av}$  value, where the mean difference for calcined magnesite was very small ( $-0.15 \text{ meq100g}^{-1}$ ) while the values were larger for dolomite ( $-0.30 \text{ meq100g}^{-1}$ ) and  $\text{MgSO}_4$  ( $-0.61 \text{ meq100g}^{-1}$ ). This suggests a link between the noticed 'release' of magnesium and change in ECEC as the order of increase in ECEC was the same as the order of increase in magnitude of 'released' Mg.

## DISCUSSION

The soils studied here, in their untreated state, certainly have low magnesium concentrations. Total concentrations fall within the low ( $15\text{-}30 \text{ meq100g}^{-1}$ ) category described by Metson and Gibson (1977). Acid extractable reserves ( $\text{Mg}_e$ ) for the two soils analyzed (Tauhara and Halls, mean  $\text{Mg}_e = 0.63 \text{ meq100g}^{-1}$ ) were well below Metson and Gibson's threshold of  $3 \text{ meq100g}^{-1}$  and were only 12-15% of Adams' (1973) suggested critical value below which he expected trees to be deficient. The Halls site had the highest  $\text{Mg}_{av}$  concentration ( $0.92 \text{ meq100g}^{-1}$ , Table 1), on the border of the low ( $0.5\text{-}1.0 \text{ meq100g}^{-1}$ ) and medium ( $1.0\text{-}3.0 \text{ meq100g}^{-1}$ ) categories. The other two soils were rated very low ( $<0.5 \text{ meq100g}^{-1}$ ) (Metson and Gibson 1977). Critical values for many crops were reviewed by Metson (1974). All critical values were below  $1 \text{ meq100g}^{-1}$ , ranging from  $0.1 \text{ meq100g}^{-1}$  up to that value. Metson also stated that the desired proportion of Mg on the exchange complex should be approximately 10%. The three soils studied here range from 2.5% to 19.2%. Soil solution Mg concentrations are low by comparison with Barber's (1984) survey of a range of agricultural soils, but were slightly higher than forest soils reported by Hunter (1991) and Meyer *et al* (1988).

The available Mg concentrations indicate that the Halls soil had higher Mg than the other two, and this would suggest that depletion of Mg levels due to pasture production was not the reason for the greater severity of deficiency in ex-pasture sites.

It is possible to manipulate magnesium availability by varying soil pH, and this has often been investigated in relation to liming of agricultural soils (Edmeades *et al* 1985, Grove *et al* 1981, Myers *et al* 1988). A decrease in exchangeable Mg due to precipitation reactions has been reported for variable charge soils, though this is normally at higher soil pHs (Sumner *et al* 1978, Edmeades *et al* 1985) although Grove *et al* (1981) found fixation to occur from pH 5.0 upwards. The mechanism they suggested was the adsorption and possible solid diffusion of Mg into newly formed hydroxy-Al polymers, as formation of  $\text{MgAl}(\text{OH})_5$  is unlikely at low pH (Hunsaker and Pratt 1971). Increasing the pH of both the Tauhara and Waimihia soils decreased the available Mg (Figure 3).

Both these soils had initial pHs of about 5, similar to the study of Grove *et al* (1981). The magnitude of the change was similar to that found in their study at approximately  $0.2 \text{ meq}100\text{g}^{-1}$  per pH unit. Why the Halls soil did not show a pH induced decrease in  $\text{Mg}_{\text{av}}$  is not clear, although it may be because there is little or no exchangeable Al for formation of such polymers. The slope of the regression lines of  $\text{Mg}_{\text{av}}$  vs soil pH for each of the soils showed an increase in b coefficient (Table 2) with increasing KCl extractable Al concentration. Both Grove *et al* (1981) and Myers *et al* (1988) showed a relation between magnesium fixed by the soil and soil exchangeable Al. However Edmeades *et al* (1985), found little or no fixation below pH 6.2 and the smallest reduction in  $\text{Mg}_\text{e}$  in the soil with the second highest exchangeable Al concentration.

Decreasing the pH of the soils increased Mg availability, and this is likely to be due to solubilisation of Mg compounds (Metson 1974). This could be of importance on soils which are marginal for Mg, where the acidification of the soil by the pines may improve the availability of Mg. Will (1960) recorded an improvement in health of Mg deficient seedlings fertilised with ammonium sulphate. Though he suspected a nitrogen response, it may have been due to a release of Mg following the acidifying effect of the fertiliser. However, the overall changes in soil Mg, (between  $0.09$  and  $0.24 \text{ meq}100\text{g}^{-1}$  per pH unit, Table 2) caused by manipulation of pH are not large enough to raise  $\text{Mg}_{\text{av}}$  concentrations above the low category of Metson and Gibson (1977). Thus Mg fertilisers are a more appropriate option.

Improvement in available Mg is possible with all three fertilisers used, at least under the conditions studied here. Soil solution Mg is most strongly affected by  $\text{MgSO}_4$  and much less by dolomite and calcined magnesite. This is important for rapid availability of Mg to the tree.  $\text{MgSO}_4$  at the higher application rates raised the  $\text{Mg}_{\text{ss}}$  concentration of these soils into and above the normal range for leached soils ( $12\text{-}49 \text{ mgL}^{-1}$ ) recorded by Barber (1984). Both dolomite and calcined magnesite treated soils remain below this range. The  $\text{Mg}_{\text{av}}$  concentrations are raised to the medium to high categories of Metson and Gibson (1977) and for all the rates and fertilisers will be above the critical values for crops summarised by Metson (1974). Acid extractable reserves, while improving by between  $0.18$  and  $0.71 \text{ meq}100\text{g}^{-1}$  over the unfertilised soils (Table 3), still remained at approximately 25% of Adams' critical value. This could have implications for the health of a long term tree crop, especially if a number of rotations are expected.

The fact that reserve Mg concentrations increased with fertiliser application (Table 3) means there must have been some fixation of Mg by the soil, or that reaction of the less soluble fertilisers was not totally complete. However, with the rates of Mg applied there is more than adequate Mg on the

exchange sites to improve the available Mg above suggested critical values. Thus fixation will be of relatively minor importance to the short term Mg supply to the tree. The noticed "release" of Mg, will however, be a bonus to the tree's requirements, and is quite a substantial contributor to the  $Mg_{av}$  concentrations. An additional  $1.29 \text{ meq } 100\text{g}^{-1}$  is in the available form when  $400 \text{ kg ha}^{-1}$  Mg was added to the Halls site for instance, boosting the application rate by approximately 30%. The release appears to be due to a combination of the pH effect of the fertiliser and the ionic strength of the soil solution following fertilisation. It cannot be due to pH modification alone as that would only account for the  $\text{MgSO}_4$  source (lowering pH and converting  $Mg_r$  to  $Mg_{av}$ ), whereas dolomite raises pH and would be expected to cause a decrease in  $Mg_{av}$ .

A central problem raised before this study was that the tree's improvement in foliar Mg concentrations and growth was only gradual after fertilisation. One possibility was that this may be due to a slow availability of the fertiliser source. These experiments have shown that the three fertilisers commonly used to treat Mg deficient *P. radiata* in New Zealand all improved the soil available Mg, though with varying effects on the equilibrium between  $Mg_{ss}$  and  $Mg_e$ . There was substantially more Mg in the soil solution when using  $\text{MgSO}_4$  compared to the other two fertilisers. This should give rise to greater plant uptake, but also more likelihood of rapid leaching loss. Will (1960) showed that most applied  $\text{MgSO}_4$  leached from a pumice soil within nine months of fertiliser application. Similar conclusions have been reached by pasture scientists working on these pumice soils (McNaught and Dorofaeff 1965). Similarly Hunter (1991) has shown a strong residual build up of  $Mg_{av}$  and Mg, five years after application of dolomite at  $400 \text{ kg ha}^{-1}$  Mg, but no detectable difference from the control where  $\text{MgSO}_4$  had been used at  $55 \text{ kg ha}^{-1}$  Mg.

All rates and types of fertiliser used here improved  $Mg_{av}$  above most crops' critical values and so it seems that the slow response of trees to applied Mg is probably due to factors other than source or rate of fertiliser. There are three possibilities. Firstly the size fraction of applied fertiliser could affect the rate at which the Mg becomes available; 2-5mm chip calcined magnesite has been used widely in Tauhara forest for instance. However field trials using dolomite have used fine powder. Secondly, the tree's physiology may limit its response physiologically or finally, competing vegetation may delay the response by modifying the soil moisture regime.

## CONCLUSIONS

The soil studied were low to very low in available Mg concentrations. Epsom salts, dolomite and calcined magnesite at rates of between 100 and  $400 \text{ kg Mg ha}^{-1}$  raised available Mg concentrations to an adequate level when compared to critical levels for a wide variety of agricultural crops. However  $Mg_r$  concentrations remained below Adams' (1973) suggested critical levels below which a deficiency would be expected, and this could have implications for the longer term. The equilibrium between  $Mg_{ss}$  and  $Mg_e$  is affected by type of fertiliser and the equilibrium can be manipulated by modifying soil pH. However pH reductions alone will not increase plant available supplies of Mg adequately to increase growth. Plant available supplies must be amended by fertiliser additions. In addition, soil acidification has been shown to increase ecosystem losses of basic cations (North East U.S.A., Europe) and certainly cannot be viewed as a long term solution to magnesium deficiencies on pumice soils.

## Chapter 3

### Movement of Mg derived from Epsom salts and calcined magnesite down a pumice soil profile

#### INTRODUCTION

A problem with the use of soluble Mg fertilisers on high rainfall sites is the rapid leaching loss of Mg from the profile. On pumice soils work has been done on pasture sites (McNaught & Dorofaeff 1965, Toxopeus & Gordon 1985). Will (1961) suggested a rapid loss of  $25 \text{ kg ha}^{-1} \text{ MgSO}_4$  from a forest nursery soil within 9 months of application, and Will and Knight (1977) studied leaching losses under a recently planted stand of *P. radiata*, and the same stand, soon after canopy closure had been attained. Such losses are important ecologically and economically and are one of the reasons less soluble sources of Mg have commonly been used in agriculture and forestry. However, in the case of *P. radiata* the uptake of soil applied Mg has been slow (Hunter 1991). One possible cause could be due to the lower solubility of sources such as calcined magnesite.

The objective of this part of the programme was to investigate the leaching and availability of various Mg sources. There were three main considerations in the design of this trial:

1. Solubility of the Mg source, ranging from highly soluble Epsom salts to the less soluble dolomite and calcined magnesite.
2. A high application rate of Epsom salts, the highest rates previously used (Hunter 1991) were  $400 \text{ kg ha}^{-1} \text{ Mg}$  as calcined magnesite and dolomite, and this had only been slowly assimilated by the tree, the same rate of  $\text{MgSO}_4$  would be used in comparison with 2-5 mm calcined magnesite chip.
3. The effects of grass growth and rainfall on Mg leaching.

This field experiment complemented the laboratory based studies discussed in Chapter 2, by measuring how solution ( $\text{Mg}_{\text{ss}}$ ) and exchangeable Mg ( $\text{Mg}_{\text{e}}$ ) concentrations changed with time and rainfall. Further the data collected was needed as input for modelling Mg uptake by the *P. radiata* on the site (discussed in Chapter 6).

#### OBJECTIVE

To determine the effect of Epsom salts and calcined magnesite on soil solution concentrations in a field experiment, and to assess the longevity of any effects of applied Mg on soil solution and exchangeable concentrations. To determine the effects of grass on such effects.



## MATERIALS AND METHODS

The experiment was situated adjacent to the field trial site in Halls block, Tauhara Forest 20 km north of Taupo. The block had been under pasture for the previous 20 years and had been planted with *P. radiata* in April 1988.

The experiment was a randomised complete block design, comprising four treatments replicated three times. The treatments were:

1.  $\text{MgSO}_4$  @ 400  $\text{kg ha}^{-1}$  Mg, no grass.
2.  $\text{MgSO}_4$  @ 400  $\text{kg ha}^{-1}$  Mg, plus grass.
3. Calcined magnesite ( $\text{MgO}$ ) @ 400  $\text{kg ha}^{-1}$  Mg, no grass.
4. A control, no grass.

Plots averaged 5  $\text{m}^2$  and were separated from each other to a depth of 1.2 metres by polythene sheeting placed in trenches between the plots. This was to stop lateral influence of any treatments. All vegetation was sprayed out, using Roundup (Glyphosate), from the plots 2 months before treatments were applied. Perennial rye grass was sown onto those plots requiring it. Weed control was maintained where required for the duration of the experiment.

Three sets of three micro suction lysimeters were installed in each plot at the depths of 5, 15 and 45 cm below the soil surface. These were combined to give one composite sample per depth per plot. Lysimeters were connected to a vacuum pump via removable sample bottles and fixed 2.5 litre vacuum reservoir bottles. Suction was applied to a maximum of 15 bar and the system left for a number of hours. Temporary sample bottles were exchanged for clean sample bottles once some solution had been obtained, and suction reapplied. The initial solution was discarded. Samples were then collected the following day, after overnight vacuum.

Provision for monitoring soil moisture was made by installing tensiometers in grassed and ungrazed plots within each block. These were installed at two depths; 10 cm to reflect conditions in the upper two lysimeters, and 45 cm to monitor the conditions at the lower lysimeter.

A thermohygrograph and rain gauge were installed adjacent to the experiment to monitor temperature, humidity and rainfall.

Fertiliser treatments were applied by hand broadcast to the soil surface in September 1989. Soil solutions were extracted at approximately 3-4 week intervals until March 1991. Weekly measurements were made of soil moisture tension, rainfall, temperature and humidity.

In March 1990, six months (181 days) after treatments were applied, ten composite 5 cm core soil samples were taken in 5 cm depth increments to a depth of 20 cm. After 18 months (548 days), when the experiment was terminated, the plots were resampled to a total depth of 50 cm. Depth increments of 5 cm were used down to 20 cm and 10 cm increments thereafter.

Soil solution samples were refrigerated following collection. Magnesium concentrations ( $Mg_{ss}$ ) were analyzed by atomic absorption spectroscopy and expressed as  $mgL^{-1}$ . Exchangeable Mg ( $Mg_e$ ) was determined by leaching 5 gram oven dry equivalents of field moist soil samples overnight with neutral 1N Ammonium Acetate (Nicholson 1984), following a preliminary rapid leaching with 20 ml 95% ethanol to remove entrained soil solution.  $Mg_e$  was expressed as  $meq100g^{-1}$  oven dried soil.

Subsamples of the soils were air dried and the pH determined in water at a soil:solution ratio of 1:2.5.

Moisture content of the soils was determined by drying to constant weight at 105°C.

## Statistical Analysis

Statistical analysis was done using the SAS system (SAS Institute 1985) using analysis of variance procedures.

## RESULTS

### Effect of Treatments on Soil Solution Mg Concentrations

A total of twelve sets of samples were collected over a period of 381 days, and these were statistically analyzed separately for each sample time and depth. It was necessary to log transform the data to standardise the variance. However, untransformed data are presented graphically for the experimental period.

For the 5 cm depth samples (Figure 1) the ungrassed  $MgSO_4$  treatment showed consistently higher  $Mg_{ss}$  ( $P < 0.05$ ) concentrations than the control. The concentration peaked at  $88.9 mgL^{-1}$  at 94 days after fertiliser application and declined exponentially thereafter to pretreatment concentrations of approximately  $1 mgL^{-1}$  by day 297. The  $MgSO_4$  plus grass treatment peaked slightly later at day 108 and the maximum concentration was approximately 75% lower than the ungrassed  $MgSO_4$ . However both treatments showed a sharp peak at day 40. The grass treatment was only significantly higher than the control at days 40 and 297. Calcined magnesite followed a similar pattern to the other treatments, reaching a peak of  $43.4 mgL^{-1}$  at day 108. However the only time this treatment was significantly higher than the control was day 345.

The control treatment also showed a peak at day 108,  $Mg_{ss}$  concentration rising from an initial  $1.57 mgL^{-1}$  to a maximum of  $20.8 mgL^{-1}$  on that date. It then declined to  $0.61 mgL^{-1}$  by day 297 and remained at approximately that level thereafter. To determine whether concentrations constituting this peak were different from the concentrations during the rest of the experiment, all data from the control plots between days 60 and 181 were compared to data outside that time by analysis of variance. This showed that  $Mg_{ss}$  concentrations between days 60 and 181 in the control treatment were significantly ( $P < 0.0001$ ) higher than the periods before and after. This peak could be due to decomposition of plant material following grass control with herbicide.

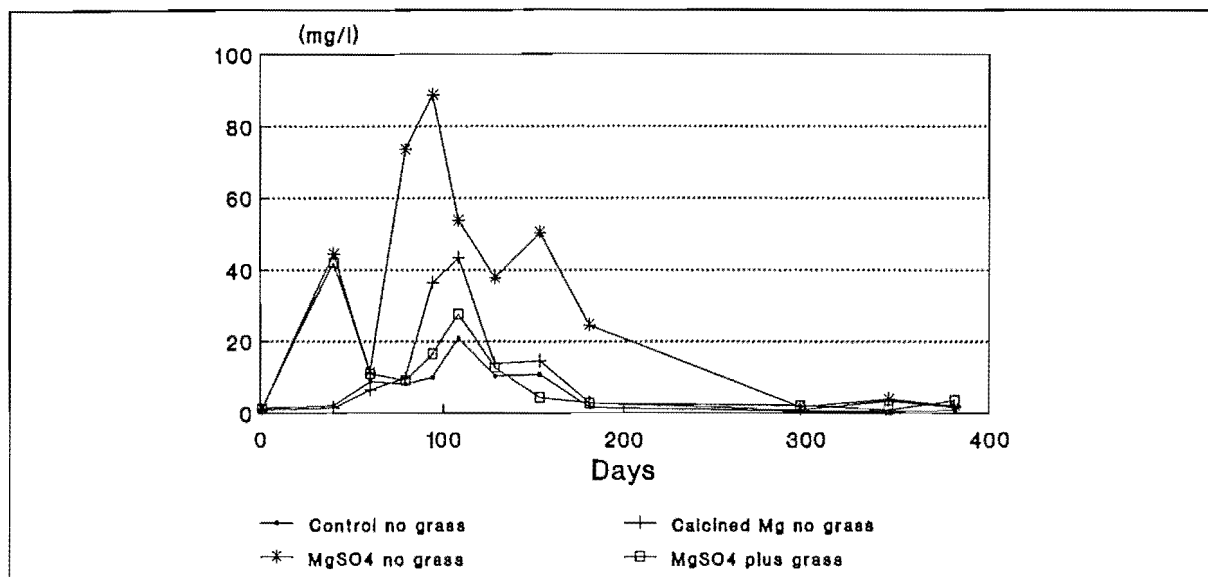


Figure 1. Changes in solution Mg concentration with time, 5 cm depth, as influenced by Mg treatment.

At the 15 cm sampling depth a sharp peak in  $Mg_{ss}$  was apparent at day 40 for both the  $MgSO_4$  and  $MgSO_4$  plus grass (Figure 2). The concentrations were very high (323.3 and 449.5  $mgL^{-1}$  respectively) and very much greater than the control ( $P=0.0001$ ). Both concentrations decreased rapidly although remaining significantly greater than the control until day 153 for the  $MgSO_4$  treatment and day 108 for the  $MgSO_4$  plus grass. It was not until day 297 however that the means of all the treatments became of a similar magnitude. At this depth there was no significant effect of calcined magnesite on  $Mg_{ss}$  at any time. The temporal fluctuation of  $Mg_{ss}$  concentration in the control occurred to a smaller extent at this depth, and peaked later than the 5 cm depth, at day 108.

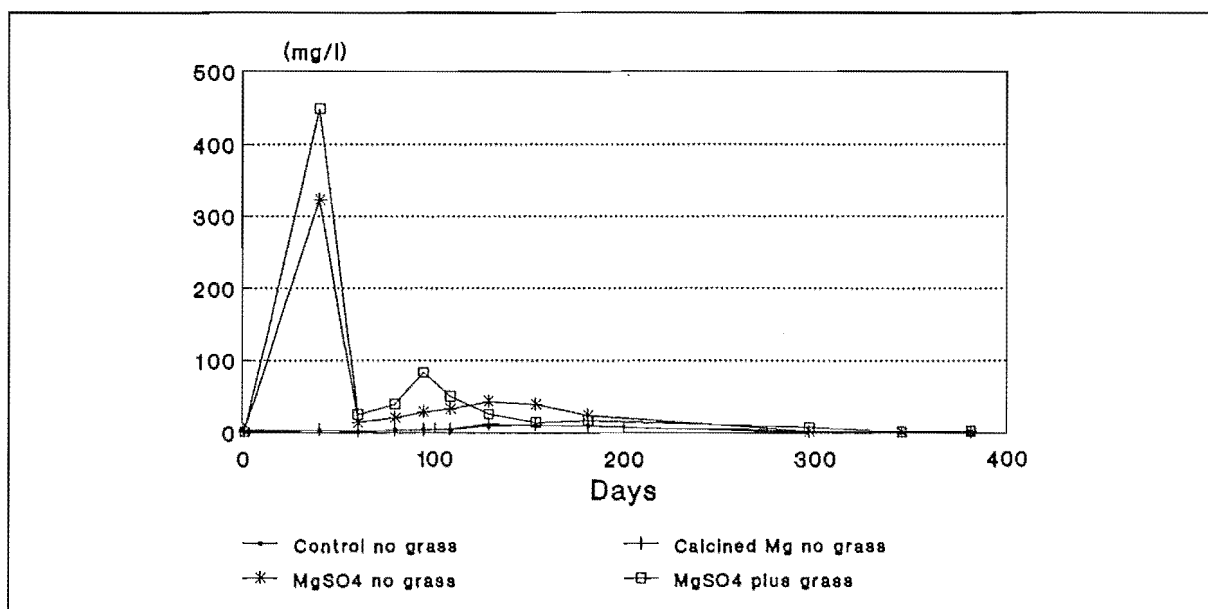


Figure 2. Changes in solution Mg concentration with time, 15 cm depth, as influenced by Mg treatment.

Unlike the shallower depths there was no peak in  $Mg_{ss}$  concentrations at day 40 at the 45 cm sample depth (Figure 3). The  $Mg_{ss}$  concentrations in the ungrassed  $MgSO_4$  treatment peaked at  $108 \text{ mgL}^{-1}$  at day 97 and decreased to reach control concentrations by day 297. The magnesium plus grass treatment peaked earlier at day 74 ( $62 \text{ mgL}^{-1}$ ) and decreased more slowly than the ungrassed magnesium treatment, to reach control concentrations at day 345. Once again the calcined magnesite treatment had no effect (Figure 3). The peak in the control treatment appeared later again than the shallower samples at day 181, and was smaller than at 15 cm depth,  $8.06 \text{ mgL}^{-1}$  compared to  $10.3 \text{ mgL}^{-1}$ .

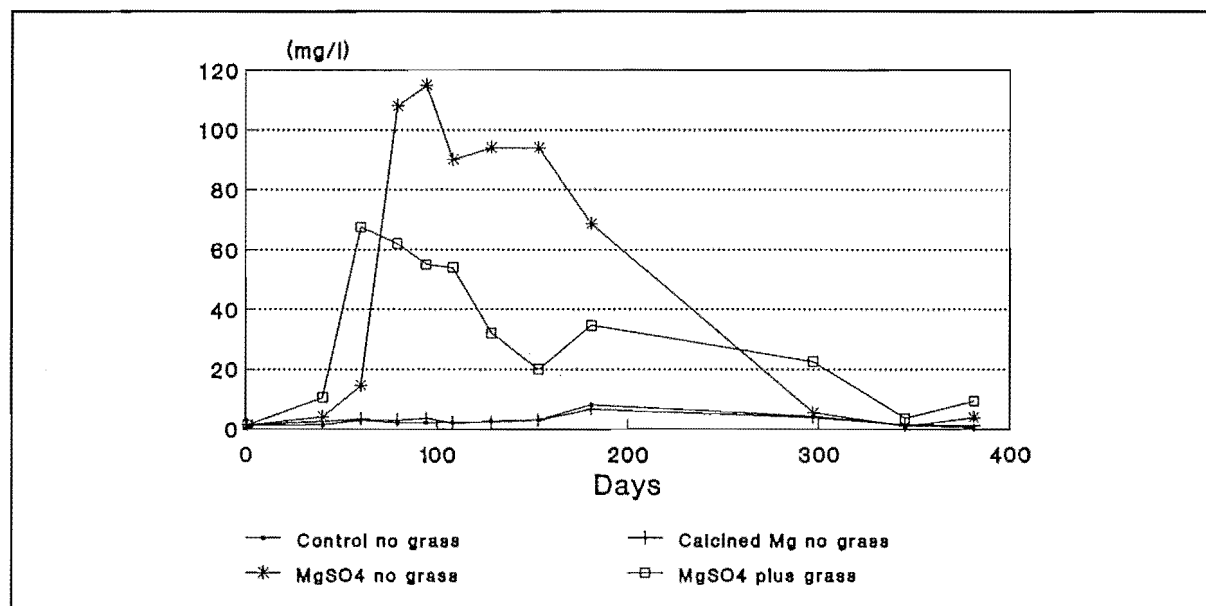
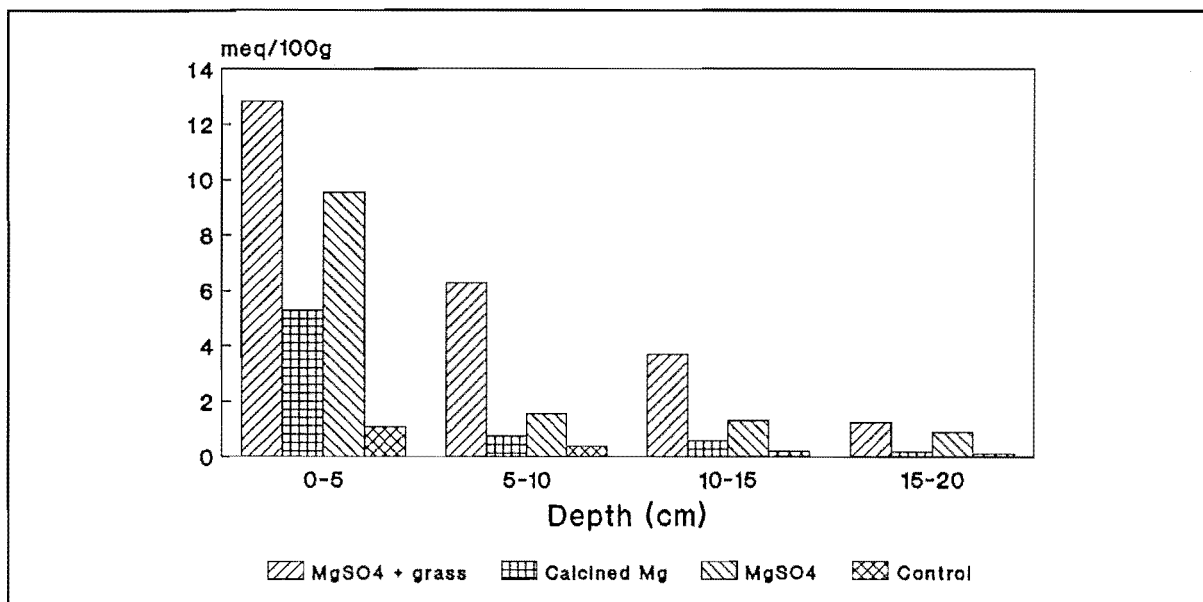


Figure 3. Changes in solution Mg concentration with time, 45 cm depth, as influenced by Mg treatment.

### The Effect of Treatments on Exchangeable Mg

All fertiliser treatments had a significant and positive effect on  $Mg_e$  concentrations after 6 months. Analysis of variance, using  $\log Mg_e$ , in a split plot model showed a significant treatment effect ( $P=0.0001$ ) and a depth effect ( $P=0.0001$ ) but no significant interaction of treatment and depth ( $P=0.0706$ ). Treatment effects were then analyzed by depth to investigate treatment effects further. Results are graphed in Figure 4 and the probability values for single degree of freedom contrasts tabulated (Table 1). All treatments improved  $Mg_e$  concentrations over the control although not at all depths. The two soluble Mg treatments had a strong effect on  $Mg_e$  compared to control levels. The effect decreased with depth; the ungrassed  $MgSO_4$  treatment decreased from  $9.35 \text{ meq100g}^{-1}$  in the 0-5 cm zone to  $0.88 \text{ meq100g}^{-1}$  at 15-20 cm (Figure 4). Calcined magnesite also significantly improved  $Mg_e$  concentrations in the top 15 cm of the soil, although not as much as the  $MgSO_4$ . Comparison of the  $MgSO_4$  treatment with and without grass cover, showed higher  $Mg_e$  concentrations in the grassed plots (Figure 4), though these were only significantly different in the 5-15 cm zone (Table 1). Apparently the grass slowed the movement of Mg down the soil profile.



**Figure 4.** Treatment effects on exchangeable Mg with soil depth, March 1990, 181 days after treatments were applied.

**Table 1.** Probability of significant single degree of freedom contrasts in exchangeable Mg sampled in March 1990, 181 days after application of treatments.

Contrast	Depth (cm)			
	0-5	5-10	10-15	15-20
Control vs MgSO <sub>4</sub> (ungrassed)	0.0001	0.0001	0.0006	0.0322
Control vs Cal. Mag (ungrassed)	0.0001	0.0100	0.0131	0.1875
Grass effect <sup>1</sup>	0.3503	0.0001	0.0356	0.4834

<sup>1</sup> Grass effect is comparison of grassed vs. ungrassed MgSO<sub>4</sub> treatments.

After eighteen months there was still a strong treatment ( $P=0.0001$ ) and depth ( $P=0.0001$ ) effect in the experiment and the treatment\*depth interaction was significant at  $P=0.0605$ . The concentrations of the treated plots had declined greatly in the preceding twelve months (compare Figure 4 and Figure 5). For example, the Mg<sub>e</sub> concentration in the ungrassed MgSO<sub>4</sub> treatment in the 0-5 cm zone, decreased from 9.35 meq100g<sup>-1</sup> to 2.78 meq100g<sup>-1</sup>.

Treatment differences were greatest in the upper horizons with the MgSO<sub>4</sub> treatment having a positive effect down to 40 cm while the calcined magnesite increased concentrations significantly down to 20 cm. The MgSO<sub>4</sub> and calcined magnesite treatments were very similar in March 1991, with the Mg<sub>e</sub> concentration higher in the latter treatment in the 5-10 cm zone (0.86 meq100g<sup>-1</sup> vs 1.93 meq100g<sup>-1</sup>). Differences between grassed and ungrassed plots treated with MgSO<sub>4</sub> were smaller than when measured at six months, and were only significantly different in the 5-10 cm zone (Table 2).

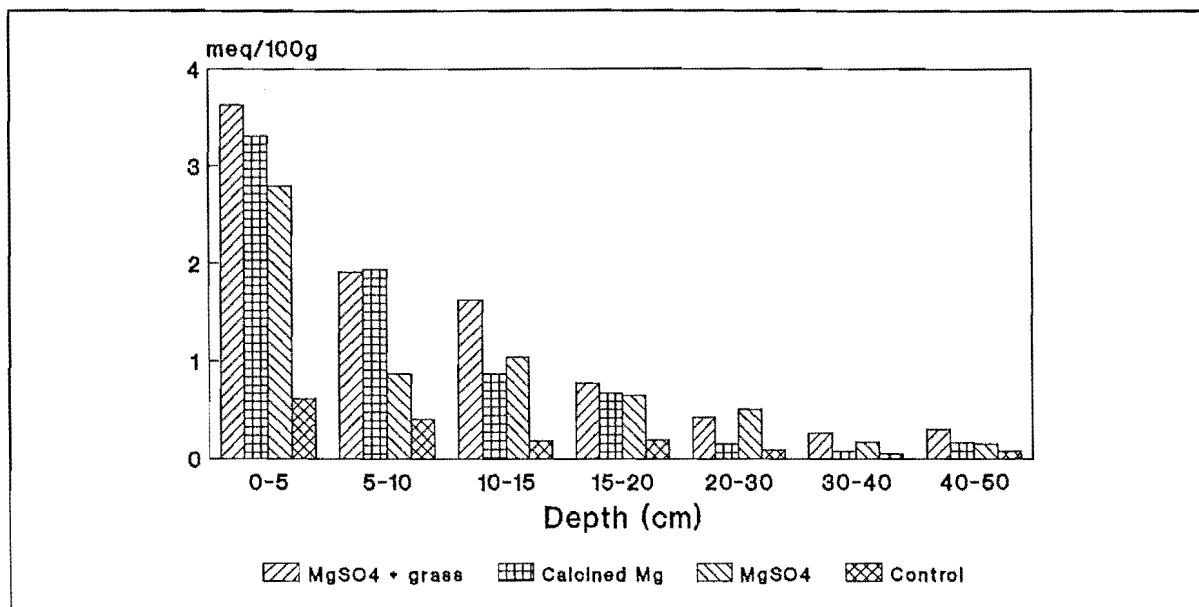


Figure 5. Treatment effects on exchangeable Mg with soil depth, March 1991, 548 days after treatment application.

Table 2. Probability of significant single degree of freedom contrasts in exchangeable Mg concentrations for selected treatments, sampled in March 1991, 548 days after treatment application.

Contrast	Depth (cm)						
	0-5	5-10	10-15	15-20	20-30	30-40	40-50
Con vs MgSO <sub>4</sub>	0.0001	0.0317	0.0010	0.0081	0.0053	0.0059	0.1767
Con vs C' Mag	0.0001	0.0008	0.0016	0.0113	0.0729	0.1922	0.3181
Grass effect <sup>1</sup>	0.0787	0.0454	0.2232	0.6761	0.6607	0.3478	0.2254

<sup>1</sup> Grass effect is comparison of grassed and ungrassed MgSO<sub>4</sub> treatments.

#### Effect of treatments on other base cations.

There was very little effect of Mg treatments on the exchangeable for K, Ca, and Na. The only significant effect was observed in the 5-10 cm depth, where MgSO<sub>4</sub> caused a decrease in Ca<sub>e</sub> ( $P=0.0684$ ), K<sub>e</sub> ( $P=0.0274$ ), and Na<sub>e</sub> ( $P=0.0103$ ) compared to the control. Calcined magnesite had no significant effect on the concentrations of the other base cations.

#### DISCUSSION

Soil solution Mg concentration at the start of the experiment was, as expected, very low compared to Barber's (1984) summary of Mg<sub>ss</sub> concentrations in agricultural soils. However the concentration was higher, at 1.25 mgL<sup>-1</sup> than Hunter's (1991) recorded 0.24 mgL<sup>-1</sup> in a severely

deficient stand of *P. radiata* planted on pumice soil. This was not unexpected as the experimental site was on a previously improved pasture soil. Sites in Germany where trees showed Mg deficiency symptoms had  $Mg_{ss}$  concentrations of  $0.2 \text{ mgL}^{-1}$  (Meyer *et al.* 1988). Very few data are available for  $Mg_{ss}$  concentrations under healthy trees, although Meyer *et al.* (1988) measured  $Mg_{ss}$  concentrations under healthy spruce trees of  $0.48 \text{ mgL}^{-1}$ .

The  $MgSO_4$  treatments were very effective in raising  $Mg_{ss}$  concentrations (Figure 1, Figure 2, & Figure 3). It would appear that there was a very high concentration in the 0-5 cm zone shortly after magnesium application, and that this peak moved down to 15 cm by about day 40, and subsequently reached the 45 cm lysimeter by between days 60 and 94. A second peak in the upper 5 cm occurred at around day 108. The rainfall pattern (Figure 6) over the period of the experiment relates well to the fluctuations in  $Mg_{ss}$  concentration and soil moisture tensions in the profile (Figure 7). For example the drop in concentration in the 0-5 cm zone at day 60 (Figure 1) can be explained by the rainfall peak of over 100 mm in the 20 days preceding sampling. At day 60, all tensiometers were at a uniformly low reading, indicating the likelihood of a saturated profile. Similarly the period of low rainfall after day 200 showed up as increased soil moisture tension in the upper 10 cm of the grassed plots. This dropped away following the subsequent period of rain around day 250, at which time all tensiometer readings were low and the soil was probably saturated again. It was by day 297 that the  $Mg_{ss}$  concentrations returned to control levels. Thus it was probably this wet period that resulted in the leaching. By that stage (day 297) 794 mm of rain had fallen since the fertiliser was applied.

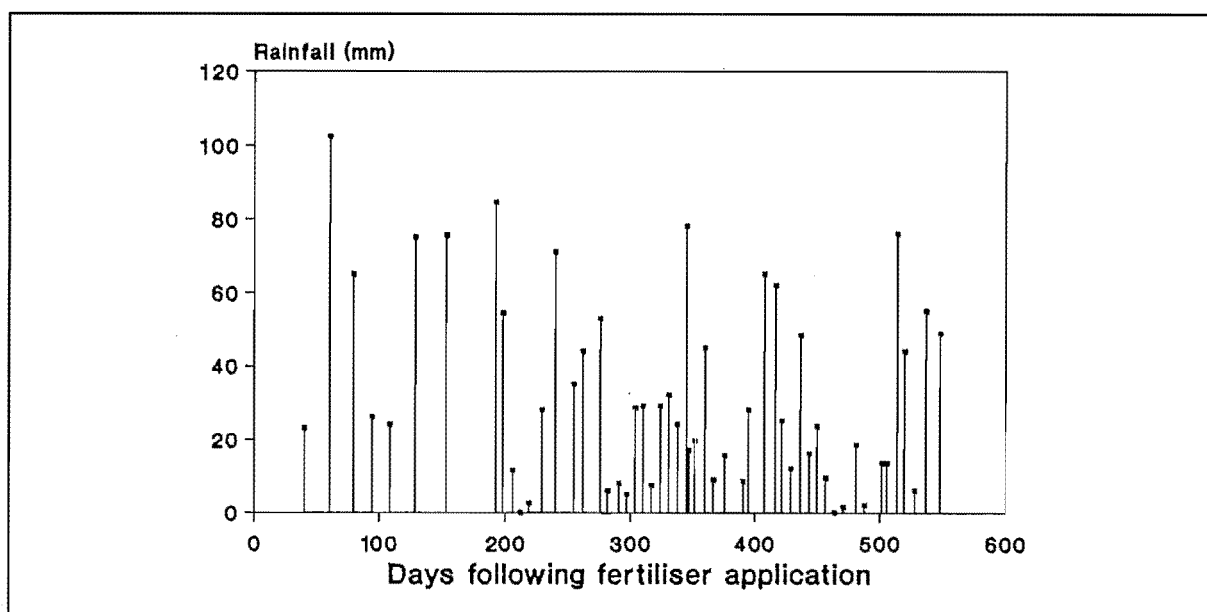


Figure 6. Rainfall data for the experimental period at Halls block, Tauhara Forest, near Taupo..

There was a difference in  $Mg_{ss}$  concentrations where grass was present, and it is likely that the drier conditions on grassed plots slowed the movement of Mg down the soil profile. Concentrations of soil solution Mg were consistently lower in the grassed plots at 45 cm depth throughout most of the experimental period. The soil moisture tensions were higher on the grassed plots, though the main effects were from day 300 onwards. The grass was unthrifty due to slow establishment for the first year, after that growth was vigorous and coupled with slightly lower rainfall showed consistently drier conditions in the grassed plots.



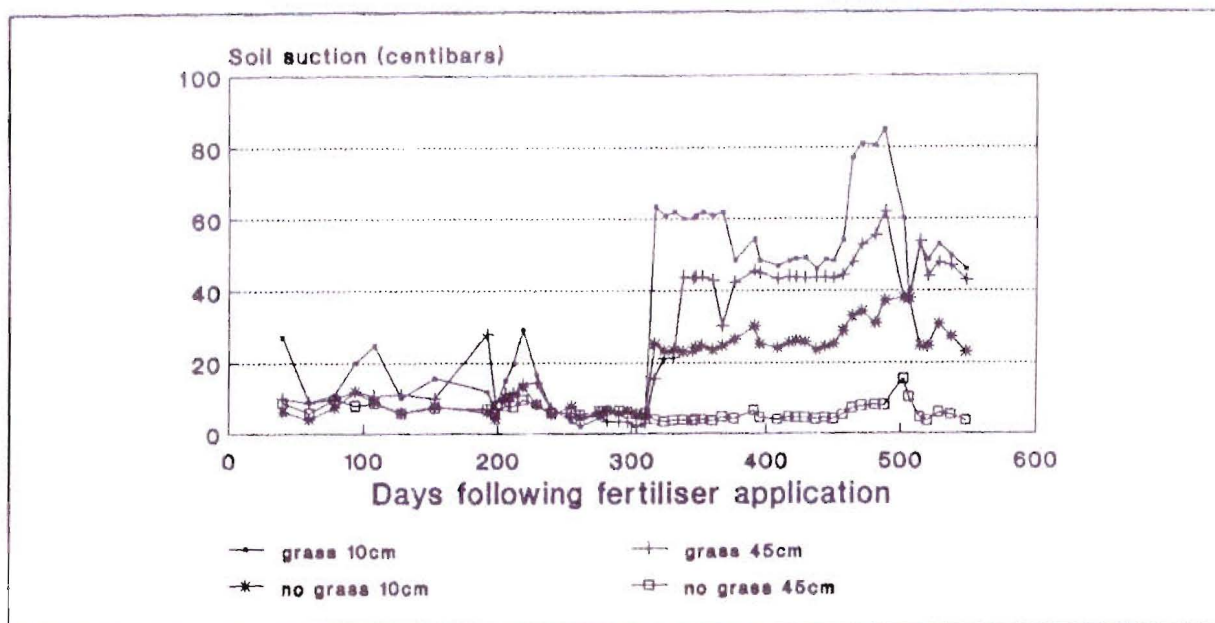


Figure 7. Soil moisture tensions in grassed and ungrassed plots, at 10 cm and 45 cm depth over the period of the experiment at Halls Block, Tauhara Forest, near Taupo.

The effect of  $\text{MgSO}_4$  on soil solution concentration was relatively short lived, and in less than 1 year concentrations had returned to their original levels. Will (1961) recorded the loss of most soil applied  $\text{MgSO}_4$  fertiliser from a forest nursery soil within nine months. Pasture research has also suggested rapid loss (McNaught & Dorofaeff 1965, Toxopeus & Gordon 1985). But during the time that the  $\text{MgSO}_4$  was effective, the concentrations were very high compared to natural conditions. Will and Knight (1977) found an optimum solution Mg concentration of  $10 \text{ mgL}^{-1}$  for *P. radiata*; concentrations in all  $\text{MgSO}_4$  treatments at all depths were well above this for most of the experimental period.

The calcined magnesite reacted differently to the soluble Mg source, having no significant impact on the  $\text{Mg}_{\text{ss}}$  concentration until day 345, and even then the increase was slight. There was a peak at day 108 at the 5 cm depth. This reaction was likely to be due to the slower solubility of the 2-5 mm chip used and the different equilibrium conditions caused by the chemistry of the reaction (see Chapter 2).

As with  $\text{Mg}_{\text{ss}}$  concentrations,  $\text{MgSO}_4$  had a strong effect on exchangeable Mg after 6 and 18 months, improving concentrations greatly. The largest influence was in the upper horizons. Grass covered  $\text{MgSO}_4$  plots had a higher  $\text{Mg}_\text{e}$  concentration than the ungrassed  $\text{MgSO}_4$  plots (Figure 4 & Figure 5). This was probably a function of the different moisture and throughflow conditions, causing a slower movement of Mg down the soil profile.

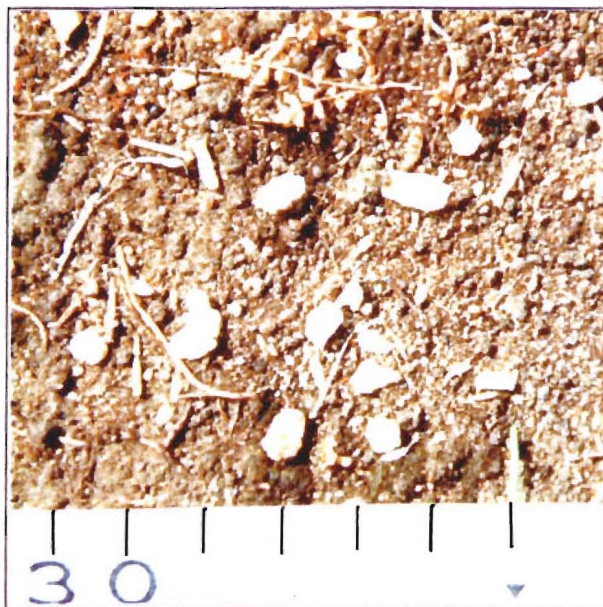


Figure 8. Calcined magnesite chips remaining on the soil surface 18 months after application. Scale in centimetres.



The calcined magnesite treatment showed a much slower release to the soil. After six months the  $Mg_e$  concentrations had improved, but only significantly in the top 5 cm of the soil (Figure 4). The effect was much smaller than the more soluble source of Mg. After 18 months, however, there was a strong effect down to 20 cm depth with concentrations being very similar to the  $MgSO_4$  treatments at that time. As the calcined magnesite chips were still very obvious on the soil surface after 18 months (Figure 8), this improvement in  $Mg_e$  is likely to be sustained.

While no direct measure of amounts of throughflow from the profile was made, it was possible to estimate leaching losses from the top 20 cm of the soil by comparing the amounts of exchangeable Mg at 6 and 18 months and assuming a soil bulk density of  $0.7 \text{ g cm}^{-3}$  (Table 3). The control treatment lost  $17.3 \text{ kg ha}^{-1}$  from the upper 20 cm of the profile over the year. This is much greater than the leaching loss of  $1.6 \text{ kg ha}^{-1} \text{ yr}^{-1}$  reported by Knight & Will (1977) under a mature stand of *P. radiata*. It is possible that most of this leaching loss was due to the decomposition of plant material following herbicide treatment of the plots, as most of the loss was from the 0-5 cm zone where the majority of the plant roots would have been located. It was not possible to partition this leaching loss into normal leaching and herbicide associated leaching as no soil samples were taken prior to herbicide treatment. Furthermore, as the soil had a history of pasture production and fertiliser additions and rainfall was greater, leaching losses are likely to be somewhat higher than found by Knight and Will (1977).

**Table 3.** Changes in  $Mg_e$  content ( $\text{kg ha}^{-1}$ ) in the upper 20 cm of the profile between March 1990 (Day 181) and March 1991 (Day 548).

Depth (cm)	Treatment			
	Control	C' Mag	$MgSO_4$ - Grass	$MgSO_4$ + Grass
0-5	-19.9	-83.7	-286.6	-392.0
5-10	0.4	51.0	-29.3	-185.4
10-15	-1.2	12.3	-11.0	-86.7
15-20	3.4	10.6	-9.7	-19.8
Total	-17.3	-9.8	-336.6	-683.9

The calcined magnesite showed a much smaller loss than the  $MgSO_4$  treated plots, which was not statistically different from the control. Though movement out of the 0-5 cm zone was large, this was offset by improvements in  $Mg_e$  contents in the lower soil horizons. It is likely that the supply of Mg from the fertiliser source was replacing and augmenting that lost from decomposition of plant material. Losses from the  $MgSO_4$  treatments were very large in comparison to the control ( $P=0.0297$  for the ungrassed  $MgSO_4$  treatment vs the control) and calcined magnesite treatments. After accounting for the amounts leached from the control, the losses for the ungrassed  $MgSO_4$  treatment were close to the  $400 \text{ kg ha}^{-1}$  applied, and greater in the  $MgSO_4$  plus grass treatment. As the period covered was 12 months, total losses over the 18 month period of the experiment will be more than calculated here. The loss of Mg from the grassed plots was greatest than from the ungrassed  $MgSO_4$  plots ( $P=0.0494$ ). This opposes the hypothesis that grass cover slows leaching. However it is likely that the leaching losses in the early stage of the experiment were greater in the ungrassed plots. The

actual  $Mg_e$  concentrations support this, with concentrations in the  $MgSO_4$  plus grass plots being higher than in the ungrassed plots (Figure 4).

The average amount of Mg available in the soil solution in the rooting zone, using a mean moisture content of 30% w.w. and soil bulk density of  $0.7 \text{ g cm}^{-3}$  were 2.25, 3.38, and  $16.17 \text{ kg ha}^{-1}$  for the control, calcined magnesite and  $MgSO_4$  treatments respectively. Annual uptake of between 5.9 and  $13.8 \text{ kg ha}^{-1}$  Mg per annum was measured by Madgwick *et al* (1977) for *P. radiata* in a healthy stand, and calculations from unpublished biomass data from Puruki experimental catchment showed a maximum annual Mg uptake of approximately  $19 \text{ kg ha}^{-1}$  (Beets unpublished data). It appears that the  $MgSO_4$  treatment could supply the majority of this directly from solution without resorting to exchangeable Mg. The control and calcined magnesite treatments should be able to supply approximately 20-30% of the requirement of  $10.5 \text{ kg ha}^{-1}$  measured in 2 to 4 year old trees (Madgwick *et al.* 1977). Aspects of uptake will be covered in depth in Chapter 4.

The control plots showed fluctuations in  $Mg_{ss}$  concentration which could be due to mineralisation of organic matter following the removal of grass with herbicide. The effect was greatest in the upper part of the profile where grass rooting will have been greatest. The peaks in concentration occur later with depth as depth increases, suggesting movement of this Mg down the profile and subsequent loss from the base of the soil column. This mineralisation effect is a potential benefit for the tree when weed control is done and in conjunction with improved soil moisture conditions will contribute to improved nutrition.

## CONCLUSIONS

Soil magnesium concentrations were substantially increased by the magnesium fertiliser treatments, although not as rapidly with the calcined magnesite treatment. Soil solution Mg concentrations peaked at concentrations of up to  $450 \text{ mg L}^{-1}$  between 60 and 108 days after  $MgSO_4$  fertiliser had been applied and then declined to control levels by day 300, by which time a total of 794 mm of rain had fallen. These high concentrations in the  $MgSO_4$  plots were associated with a high leaching loss from the upper 20 cm of the profile. Calcined magnesite caused less of an improvement in  $Mg_{ss}$  concentrations.

Soil exchangeable Mg concentrations were raised dramatically by the  $MgSO_4$  treatments and to a lesser extent by the calcined magnesite treatment. This effect being due to a slower reaction with the soil. Leaching losses estimated by differences in exchangeable Mg over the period were larger for the  $MgSO_4$  treatments. Grass cover appeared to slow leaching loss from the profile. Leaching losses from the calcined magnesite plots were not significantly different to the control plots.

A pulse in available Mg due to decomposition of organic matter following herbicide treatment was measured, and this caused higher leaching losses compared to published figures from an untreated stand on similar soils in the vicinity (Knight & Will 1977).

There is no obvious reason why  $MgSO_4$  fertilised trees should not be able to access the high concentrations of available Mg; adequate Mg was available in the soil solution to provide for young trees' requirements. In the first six months after application  $Mg_e$  concentrations were mainly increased in the top 5 cm of the soil. A slow plant uptake of Mg might be expected with this treatment if the site was prone to drought, or other vegetation was competing for the Mg in that zone.

## Chapter 4

### Application of Magnesium Fertilisers to *P. radiata* Planted on Pumice Soils

#### GENERAL INTRODUCTION

This chapter has three objectives:

1. To determine how quickly Mg can be assimilated by young and old trees when fertiliser is applied (objective 3, Chapter 1).
2. To study the effect of grass competition on tree growth and Mg uptake (objective 4).
3. To determine what effect other nutrients have on the magnesium nutrition of *P. radiata* (objective 6).

The chapter is therefore split into three sections. The first deals with juvenile radiata pine planted on Hall's block. It covers the effect of soluble magnesium fertiliser and grass competition on tree growth, biomass production and foliage chemistry. The second part is also based on the Halls site, but covers the effects of types of magnesium fertiliser and other elements on tree growth and foliage chemistry. These treatments were without grass competition. The third part, at Kiorenu, concentrates on the effect of soluble Mg applied to an 8 year old stand of *P. radiata*, on foliage chemistry and tree growth.

#### OVERVIEW OF EXPERIMENTATION

Some aspects of experimentation were common to more than one section of the chapter. A general overview of the experimentation is therefore presented in this introduction. The main experimental site was at Halls block. One experiment was established. It comprised a factorial layout of magnesium and boron fertiliser and grass cover, with four replicates as follows:

- 0 and 400 kg ha<sup>-1</sup> Mg, as MgSO<sub>4</sub>·7H<sub>2</sub>O (Epsom salts).
- Presence and absence of perennial Rye grass.
- 0 and 4 kg ha<sup>-1</sup> B, as H<sub>3</sub>BO<sub>3</sub> (Boric acid).

In addition four replicates of two other treatments were included in the trial:

- 400 kg ha<sup>-1</sup> Mg, as 2-5 mm chip calcined magnesite (MgO).
- A Total Fertiliser (Nitrophoska Blue) @ 50 kg ha<sup>-1</sup> P, with additional Epsom salts to raise the Mg application rate to 400 kg ha<sup>-1</sup> Mg.

Both these treatments were ungrassed.

The experiment was analysed as a factorial for investigation of the effects of  $\text{MgSO}_4$ , grass and Boron. The Mg and grass effects are presented in Section I of this chapter, as these were the main treatments of interest in the study. The boron responses, effects of other elements and types of Mg fertiliser are covered in Section II

The additional treatments were combined with the ungrassed zero and  $400 \text{ kg ha}^{-1}$  Mg as  $\text{MgSO}_4$ , and those treatments statistically analysed as a separate sub experiment to assess effects of types of Mg and other elements on foliage chemistry and tree growth.

The second experiment, at Kiorenu, was a factorial with three replicates. Treatments were:

- 0 and  $400 \text{ kg ha}^{-1}$  Mg, as  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (Epsom salts) applied to the soil.
- 10 grams Mg (as  $\text{MgSO}_4$ ) applied per tree in solution as a foliar spray.

The results from this experiment are covered in Section III.

## I. Application of $\text{MgSO}_4$ to Juvenile *P. radiata* in Combination with Grass Competition

### INTRODUCTION

The increased severity of magnesium deficiency on ex-pasture sites was one of the main problems to be addressed in this thesis. Sites with substantial grass cover had been regularly identified as strongly deficient but the reasons for this were unclear. Chapters 2 and 3 addressed the reaction of various Mg fertilisers with three soils, two of which had a history of pasture production. Plant available Mg concentrations in soils under pasture were no different to soil with no previous history of pasture production. Fertiliser reactions were similar, fertilisers raised available Mg levels sufficiently for good growth, and this effect was long lived. Therefore availability of Mg in these soils did not seem to be a problem, but the effect of the grass itself was still in question.

Effects of grass on tree growth could be due to two main factors; competition for magnesium, and competition for moisture. The increased Mg deficiency symptoms could be an indicator of this competition. The application of high rates of Mg to raise soil levels into sufficiency would lessen competition for Mg provided the overall levels were well above that required for each crop's annual uptake. If, in such a case, a deficiency still existed this could be a consequence of competition for moisture. Both trees and pasture have most of their feeder roots in the upper 20 cm of the soil profile and so are likely to be in direct competition for moisture. A lack of moisture would influence the uptake of Mg, partly due to differences in Mg transport within the soil. A more detailed discussion of this will be presented in Chapter 6.

This chapter quantifies the effect of grass competition on tree growth and Mg uptake. Preventive treatment of juvenile trees before Mg deficiency developed had been shown to work on forest sites (Hunter 1991). However such treatment had not been tried on ex-pasture sites where grass was present. Preventive treatment should lessen or remove deficiency, as Mg would be in adequate supply whether in the presence of grass or not. Therefore a treatment, using a soluble source of Mg, in conjunction with grass competition was planned.

### OBJECTIVE

To determine the effect of application of a soluble source of magnesium and grass competition on tree growth and Mg uptake in juvenile *P. radiata*.

### MATERIALS AND METHODS

#### Field Experiment

A field trial was established on Hall's block, Tauhara Forest in August 1989. The site had been used for pasture production for approximately 20 years, and was planted with *P. radiata* in April 1988. The trial was designed to investigate the effect of magnesium, grass and boron in factorial combination on tree growth. The treatments were replicated four times, in a fully randomised design. Plot size was

20 m \* 7 m, tree stocking density was 2145 stems $\text{ha}^{-1}$ . Each plot had between 10 and 15 measured inner plot trees and at least 1 row of surround trees. Treatments used were:

- 0 and 400 kg $\text{ha}^{-1}$  Mg as  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (Epsom salts).
- presence and absence of perennial rye grass.
- 0 and 4 kg $\text{ha}^{-1}$  B as  $\text{H}_3\text{BO}_3$  (Boric acid).

The treatments were applied in September 1989. Only the effects of the combinations of magnesium and grass will be discussed in this section, boron responses are covered in Section II of this chapter.

## Measurements

Height and root collar diameter were measured on labelled inner plot trees in September 1989, March 1990, September 1990, and finally March 1991. Current mature foliage was sampled at these times from each inner plot tree and bulked by plot. Samples were taken from the top third of the crown, from two primary branches.

## Tree Biomass Procedures

At establishment of the trial, the tree population was divided into five size classes and two randomly selected trees from each size class were biomassed. Weights and nutrient contents of needles, stem and roots were determined. The relation between these fractions and tree volume index ( $\text{d}^2\text{h}$ ) was used to predict the mean biomass and nutrient contents on the site at initiation of the experiment.

In March 1991, 18 months after treatment, tree biomass was estimated from the following treatments:

- 0 Mg plus grass (Control).
- 0 Mg without grass.
- 400 Mg plus grass.
- 400 Mg without grass.

These treatments were all without boron application. Four replicates of each treatment were sampled except in the case of the control where only one replicate could be sampled due to time constraints on the field work. A stratified random sampling strategy was used, selecting one tree from each of three volume index ( $\text{d}^2\text{h}$ ) classes (small, medium, and large) within each plot (Madgwick 1981). Trees were felled and divided into foliage (all ages combined), branches, and stem. Fresh weights were recorded in the field. The components were subsampled for dry weight determination. Approximately 2 kg subsamples were taken of foliage and branches; the stem was subsampled by cutting 2 cm discs at 20 cm intervals down the stem and combining the discs for drying. Tree stumps were excavated and roots severed at the stump.

Subsamples were taken to the laboratory for further processing. Final results were expressed in kg $\text{ha}^{-1}$  after converting the results for the three trees sampled to plot means using the basal area ratio (BAR) method of Madgwick (1981).

## Root Sampling

Tree roots in all four replicates of the four treatments were sampled in March 1991. Soil samples of 15 cm \* 15 cm \* 20 cm depth were taken in random directions from four inner plot trees, at two distances, 30 cm and 100 cm from the trunk, yielding a total of 8 samples per plot. Six months previously, in September 1990, a similar sampling was done the ungrassed 0 and 400 kg ha<sup>-1</sup> magnesium plots. Tree roots were separated from the soil in the field, bagged and removed to the laboratory for further processing.

## Grass Biomass

Grass biomass was sampled prior to sampling the soil by clipping all foliage on 50 cm \* 50 cm quadrats at the same sample locations used for the tree roots. Grass rhizome and roots were separated from the soil samples in the field, bagged and returned to the laboratory for determination of weights and root lengths.

## Chemical Analysis

### *Foliage and Biomass Samples*

Tree biomass samples were separated into foliage, branches, stem, stump, and the root diameter classes of >5 mm, 2-5 mm, 1-2 mm, and <1 mm. Grass biomass was separated into tops, rhizomes and root fractions. All plant material was oven dried to constant weight at 70°C, weighed, ground by a combination of Wiley Mill and ring grinder, and pelleted. The dry weight of 50 individual needles was recorded for each foliage sample. All samples were analyzed for the elements Ca, K, Mg, Na, P, S, Si, Al and Cl by X-ray fluorescence spectroscopy. Boron analysis was done on the September 1990 foliage samples by dry ashing and colorimetric curcumin method (Nicholson 1984).

### *Root Samples*

Root samples (tree and grass) were processed by washing through nested 1 mm and 2 mm sieves. Root lengths were measured using Newman's line intersect technique (Bohm 1979) for each diameter class. Results were expressed as  $L_v$  (cm cm<sup>-3</sup>). Plot means (kg ha<sup>-1</sup>) for root biomass were calculated by weighting the samples based on their distance from the trunk and hence the percentage area of the plot they would represent. Mycorrhizal root tips were counted on a sub sample of each root system from the March 1991 sampling and expressed as number per cm<sup>3</sup> of soil. Roots were then dried and processed and analyzed for nutrient concentrations as described above.

## Presentation of Data

Tree biomass data was expressed as kg ha<sup>-1</sup> oven dry weight for each component. Results for above ground components were converted to plot means using the basal area ratio (BAR) of Madgwick (1981). In this, the basal area to dry weight ratio of the sampled trees was calculated, and this ratio used to estimate biomass for the plot using the plot basal area (Equation 1).

$$W = (B_p * (\sum w_c / \sum b_i)) * \text{Stocking} \dots\dots\dots (1)$$

Where: W = plot component weight  
 $B_p$  = plot mean basal area  
 $w_c$  = component weight for sample tree  
 $b_i$  = basal area of sample tree

Grass biomass was expressed as  $\text{kg ha}^{-1}$  for each component, after converting the subsample weights to a per hectare basis.

### Statistical Analysis

Tree growth data were analyzed at each measurement period, using ANOVA, to determine treatment effects on tree height (h), root collar diameter squared ( $d^2$ ), tree volume index ( $d^2h$ ), biomass and Mg content. Where appropriate the initial values of these variables were used as covariates. Biomass and Mg content data were log transformed to standardise the variance. The analysis for biomass and Mg content of biomass fractions was unbalanced as only one of the four replicates of the zero Mg plus grass treatment was sampled.

In addition, to look at the capture of the site by the roots, the root data were analyzed in a split plot design with distance from the trunk (30 cm and 100 cm) as subplots.

Foliage data were analyzed using an ANOVA. In addition the relationship between nutrient concentration, content and needle weight was investigated using vector analysis (Timmer & Stone 1978, Weetman 1989). The direction of the shift in concentration and nutrient content compared to the control was used to interpret the effect of the treatment (Figure 1).

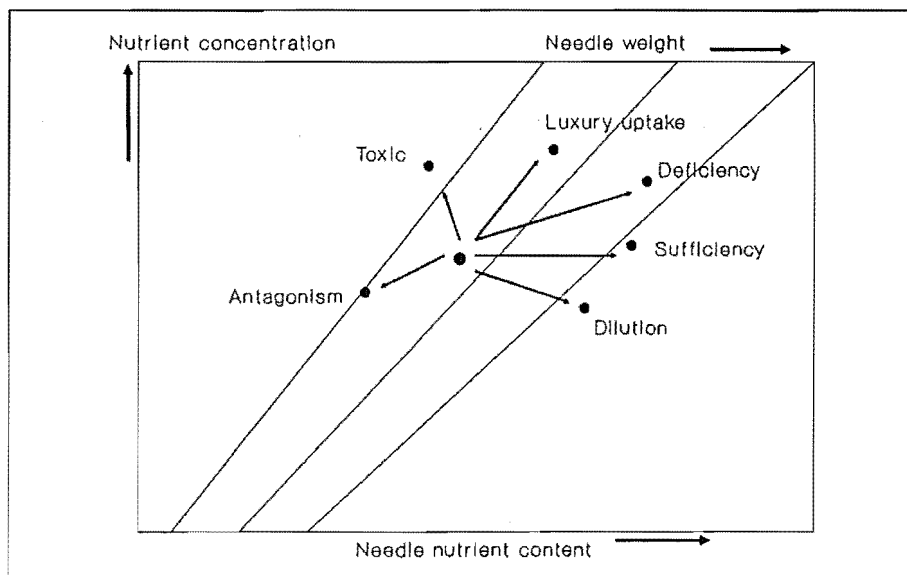


Figure 1. Examples of changes in foliar nutrient concentrations, content and needle weight and possible interpretations of the directions of the shift.



## RESULTS

### Treatment Effects on Foliage Variables

#### (i) Foliage Mg and weight.

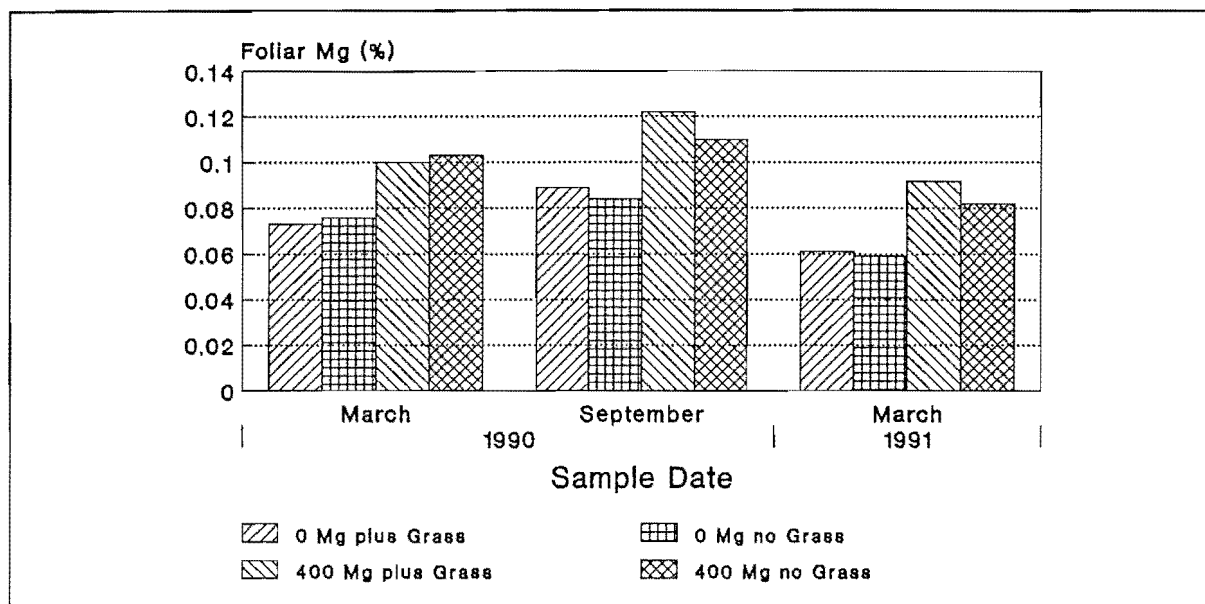
Foliar magnesium concentrations were strongly increased within six months ( $P=0.0001$ , Table 1) by the application of Mg fertiliser, with a mean concentration of 0.101% compared to 0.074% in the unfertilised plots. This improvement continued in the subsequent foliage sampling periods (Figure 2). Grass had no significant effect on foliar Mg in March 1990, but increased the concentration in September 1990 and March 1991 ( $P=0.0129$  and  $P=0.0147$ ). Needle weight was unaffected by magnesium application, however, grass decreased needle weight at all sample times (Table 1), with a decrease in the weight of 50 needles of between 0.11 grammes (March 1990) and 0.25 grammes (March 1991) on plots with grass cover.

**Table 1.** Effect of magnesium and grass treatments on foliage Mg concentration (%) and weight of 50 needles (grammes), March 1990 to March 1991. Main effect means, probabilities and standard error.

Treatment	Sampling Date					
	March 1990		September 1990		March 1991	
	%Mg <sup>1</sup>	Needle wt	%Mg	Needle wt	%Mg	Needle wt
0 Mg	0.074	1.306	0.086	1.505	0.060	1.520
400 Mg	0.101	1.329	0.116	1.542	0.087	1.584
- Grass	0.089	1.376	0.096	1.640	0.070	1.677
Grass	0.086	1.259	0.106	1.404	0.077	1.427
Significance	Probability > F					
Mg	0.0001	0.5952	0.0001	0.5668	0.0001	0.2172
Grass	0.2815	0.0090	0.0135	0.0010	0.0165	0.0001
Mg*Grass	0.9246	0.1715	0.3431	0.7095	0.1180	0.3848
Std Error	0.0037	0.0579	0.0047	0.0932	0.0033	0.0732

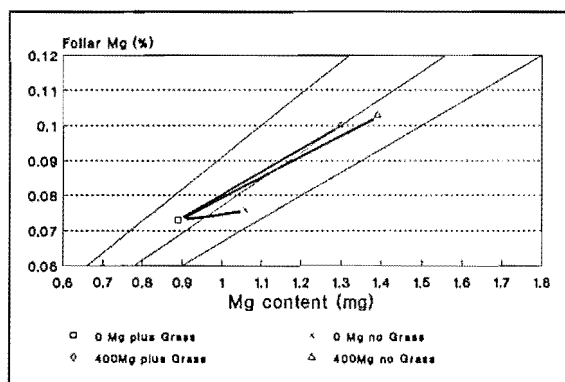
<sup>1</sup> Critical level for *P. radiata* is 0.07% (Will 1985)

The unfertilised trees on the site which had marginal foliar Mg concentrations six months after fertiliser application, improved slightly by September 1990, and were strongly deficient by March 1991. By contrast the fertilised plots had adequate concentrations in 1990, but were beginning to decline by March 1991.



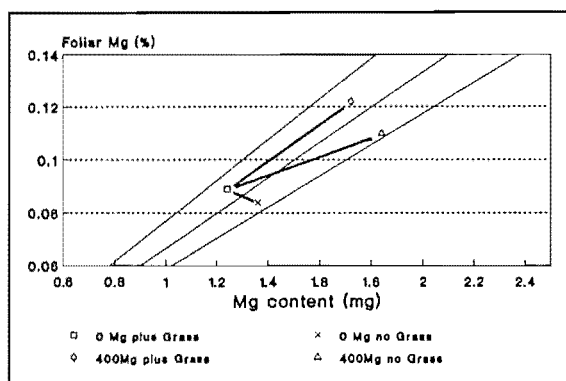
**Figure 2.** Effect of magnesium and grass treatments on foliage Mg concentrations (%) from March 1990 to March 1991 for treatment combinations.

The type of response was described using vector analysis. Plots of needle Mg content vs foliar concentration are shown in Figure 3, Figure 4, and Figure 5. The zero magnesium plus grass was the control treatment, as this is the standard condition. Treatments such as fertiliser, and grass control will modify these conditions.

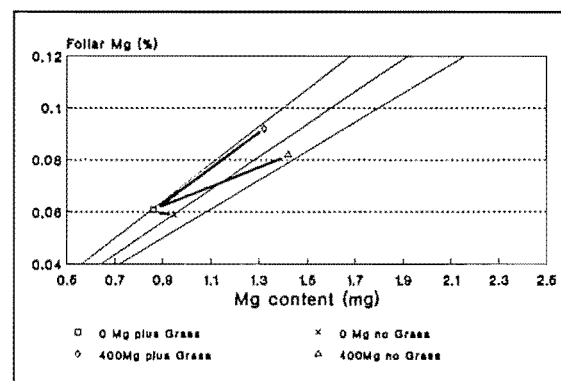


**Figure 3.** Vector analysis of the effect of magnesium and grass treatments on foliage Mg concentration and needle content, March 1990.

The vector resulting from adding magnesium without controlling grass cover indicated correction of a slight Mg deficiency in March 1990, but solely luxury uptake in September 1990 and March 1991. When Mg was added in conjunction with grass control the increase in foliar Mg concentration was slightly less than without grass control. This was probably due to a slight dilution caused by an increase in needle weight. Consequently foliar Mg content was improved in September 1990 and March 1991. When Mg was added in conjunction with grass control the increase in foliar Mg concentration was slightly less than when adding Mg without grass control. This was probably due to a dilution caused by an increase in needle weight and consequent improvement in needle Mg content. Grass control in the absence of Mg fertiliser indicated a slight deficiency in March 1990, but in September 1990 and March 1991 grass control resulted in a dilution of Mg in the needle, suggesting Mg was not limiting at these times. This is likely to be the case in September 1990, when Mg<sub>i</sub> concentrations are all above 0.08%, but is surprising in March 1991 when concentrations in the zero Mg plots are well below the critical value of 0.07% (Table 1). This could suggest that critical levels may be lower than are currently recommended.



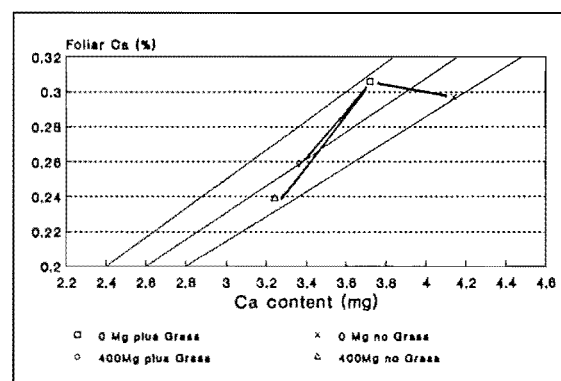
**Figure 4.** Vector analysis of the effect of magnesium and grass treatments on foliage Mg concentration and needle content, September 1990.



**Figure 5.** Vector analysis of the effect of magnesium and grass treatments on foliage Mg concentration and needle content, March 1991.

## (ii) Effects of Treatments on Other Foliar Nutrients

The effects of magnesium and grass were greatest on foliar Ca, S and Al. Summarised probabilities of treatment effects on the foliar variables are shown for the three sampling periods in Table 2. Calcium concentrations were decreased by application of Mg fertiliser, by an average of 0.07%. But the concentrations increased on grassed plots. However all foliar Ca concentrations were well above the critical value of 0.10 (Will 1985) and so these changes were unlikely to affect growth. Vector analysis (Figure 6) indicated that the effect of both treatments caused a dilution effect, further suggesting that Ca is non limiting in any of these treatments.



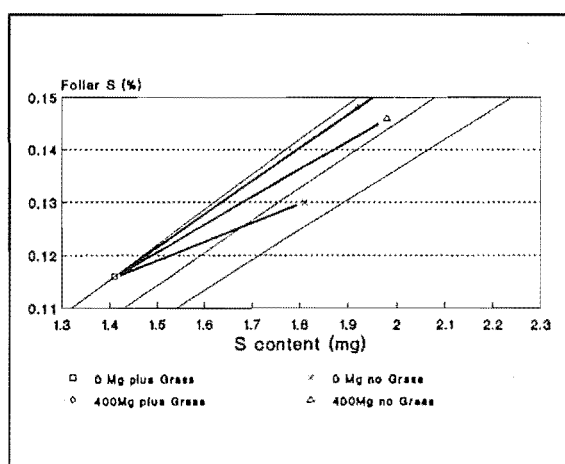
**Figure 6.** Vector analysis of the effect of magnesium and grass treatments on foliage calcium concentration and needle content, March 1990.

The results for sulphur were different from the calcium results. As sulphur is a component of the Mg fertiliser, addition of Mg caused a mean rise in  $S_i$  concentrations of 0.016% (Table 2) over the study period. On the vector plots (Figure 7, Figure 8 & Figure 9) this shift was not linked to any change in needle weight, and hence signified luxury uptake. The interaction of grass with Mg addition, showed interesting changes. In both March 1990 and March 1991 removal of grass competition caused an increase in both  $S_i$  and needle sulphur content, indicating S supply could be limiting growth at those times. By contrast removal of grass competition in September 1990 caused a dilution of the sulphur pool in the needles, indicating an adequate supply of the element at that time. As the  $S_i$  concentrations in the control (zero Mg plus grass) are 0.136%, and are well above the published critical level of 0.12%, this conclusion is likely. Both K and P concentrations were above critical levels and therefore adequate for growth.

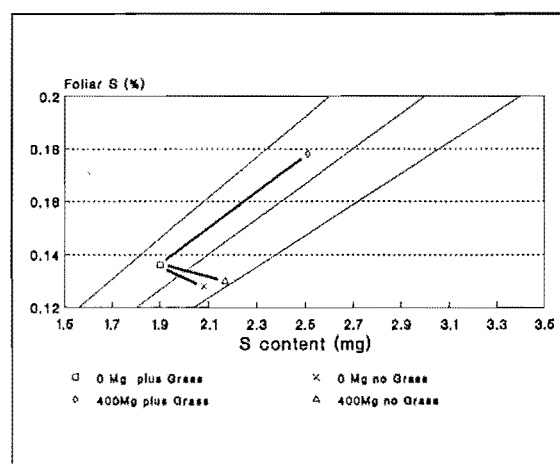
**Table 2.** Probabilities of treatment effects of magnesium and grass on foliar Ca, K, P, S and Al concentrations. Superscripts I and D signify increase or decrease of concentration caused by treatment.

Date	Treatment	Treatment Probabilities > F				
		Ca	K	P	S	Al
March '90	Mg	0.0001 <sup>D</sup>	0.4427	0.6291	0.0001 <sup>I</sup>	0.7564
	Grass	0.2246	0.0013 <sup>D</sup>	0.6506	0.1856	0.0243 <sup>I</sup>
	Mg*Grass	0.6127	0.9253	0.4519	0.0733	0.7564
	Std error <sup>1</sup>	0.0162	0.0635	0.0057	0.0064	0.0028
Sept '90	Mg	0.0001 <sup>D</sup>	0.4458	0.7083	0.0083 <sup>I</sup>	0.6762
	Grass	0.0059 <sup>I</sup>	0.0051 <sup>I</sup>	0.0100 <sup>I</sup>	0.0012 <sup>I</sup>	0.0033 <sup>I</sup>
	Mg*Grass	0.4650	0.4036	0.6816	0.0146	0.3852
	Std error	0.0265	0.0294	0.0094	0.0106	0.0045
March '91	Mg	0.0001 <sup>D</sup>	0.1731	0.2997	0.0007 <sup>I</sup>	0.9278
	Grass	0.0001 <sup>I</sup>	0.0673 <sup>D</sup>	0.1180	0.4734	0.0006 <sup>I</sup>
	Mg*Grass	0.2683	0.1182	0.3254	0.0489	0.2666
	Std error	0.0121	0.0321	0.0063	0.0029	0.0025

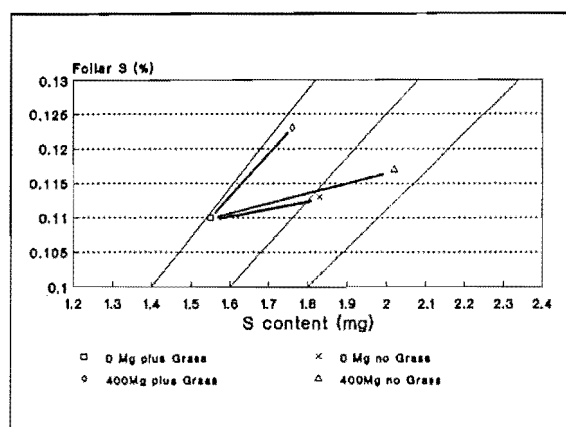
<sup>1</sup> Standard error included in table for each element at each sampling date.



**Figure 7.** Vector analysis of the effect of magnesium and grass treatments on foliage sulphur concentration and needle content, March 1990.



**Figure 8.** Vector analysis of the effect of magnesium and grass treatments on foliage sulphur concentration and needle content, September 1990.



**Figure 9.** Vector analysis of the effect of magnesium and grass on foliage sulphur concentration and needle weight, March 1991.

Diagnosis of a deficiency using critical levels based on these sample data would suggest that the unfertilised plots were marginally deficient in Mg in March 1990 and strongly deficient in March 1991, but adequately supplied in September 1990. The fertilised plots had adequate levels of Mg over the whole period. This means that rapid uptake of soluble sources of Mg is possible within six months of fertilisation. The slow response of the trees to Mg noticed elsewhere (Hunter 1991) is likely therefore to be due to the solubility/rate of availability of the source rather than a problem with the tree's physiology.

Where grass is not controlled the added Mg had only a very small or no effect on needle weights (March 1990), and so it may be that no growth response is to be expected due to Mg application, but that the main effect on growth will be due to grass control where the shifts on the vector plots showed an increase in both needle weight and Mg content. Study of the Mg<sub>i</sub> concentrations indicated that concentrations in the grass treatments were higher than in the ungrassed treatments in September 1990 and March 1991. Based on foliar Mg concentrations alone it would appear that grass control increased the deficiency. This was not the case however. The dilution effect, following improved needle weight caused by grass control, led to a lower Mg<sub>i</sub> concentration but actually a higher needle Mg content. The dilution may either be due to the rate of growth of the tree exceeding the soil's rate of supply, or the tree's rate of assimilation of Mg. In the grassed plots with a slower growth rate, the trees are able to maintain a higher Mg<sub>i</sub> concentration. The possibility of a sulphur deficiency is interesting, as growth limitation caused by this element has not been suggested before this.

We can conclude from these foliage data that addition of Mg fertiliser without controlling grass competition at the same time improves the overall Mg concentration of the foliage, but seems unlikely to result in a growth response. Grass will therefore be limiting the growth due to some other mechanism. However the higher Mg<sub>i</sub> concentrations will be useful as a buffer mechanism to prevent future growth limitation due to Mg shortage. If grass is controlled and Mg added there is an improvement in needle Mg content over and above the increase in content caused by fertiliser alone. This will further improve the buffer against pruning shock or other limitations to uptake such as drought.

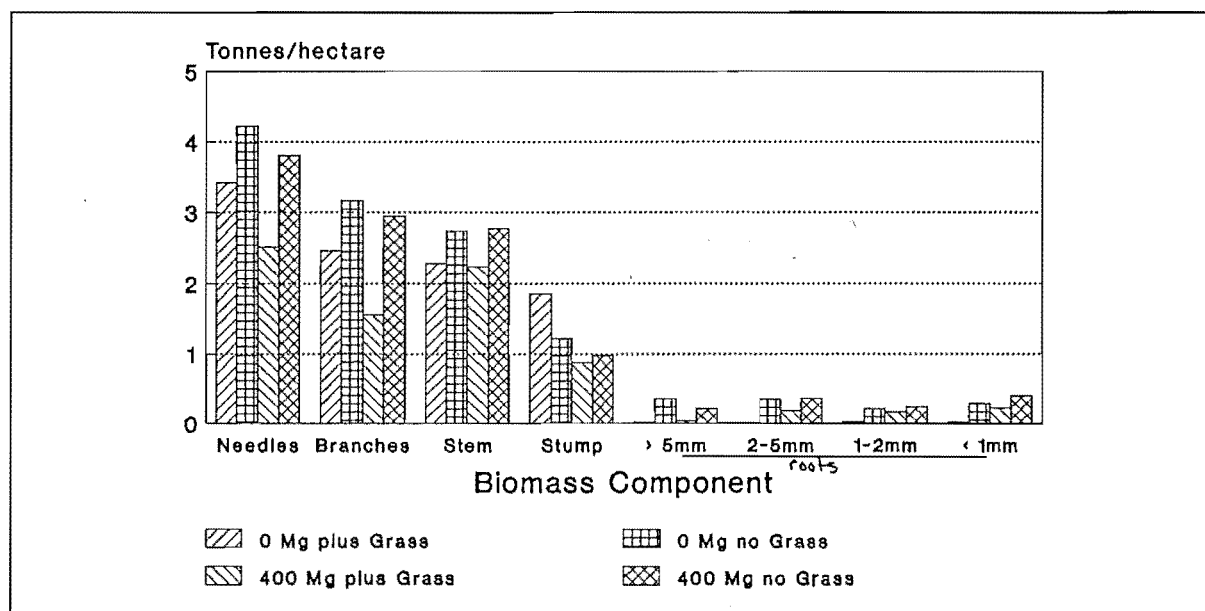
### Effect of Magnesium Fertiliser and Grass on Tree Growth

Magnesium fertiliser had no effect on tree height, root collar diameter<sup>2</sup>, or volume over the period of time that measurements were taken, except for a transitory increase in height in the six month period following fertilisation. At that time the mean height in the fertilised plots was 5.3 cm greater than in the unfertilised plots ( $P=0.0395$ ). This response was supported by the interpretation of the vector analysis of the foliage data for the period, where a shift indicating deficiency was detected (Figure 3). The difference had disappeared when the trees were next measured in September 1990. Treatment means adjusted by the relevant covariate are summarised in Table 3.



**Table 4.** Effects of Mg and grass on the dry weights of the various biomass components sampled in March 1991, 18 months after treatment. Trees 3 years old. Main effect means presented are least square means, calculated as design was unbalanced.

Treatment	Biomass Fraction, Kgha <sup>-1</sup>								
	Above Ground			Below Ground					Total
	Needle	Branch	Stem	Stump	>5mm	2-5mm	1-2mm	<1mm	
0Mg	3819.1	2811.0	2499.5	1532.3	193.5	182.9	120.9	157.0	11570
+Mg	3160.2	2253.3	2499.9	926.8	126.7	273.3	204.4	314.3	9967
-Grass	4014.5	3054.7	2749.9	1095.2	288.1	356.9	226.9	343.9	12374
Grass	2964.8	2009.7	2249.5	1363.8	32.1	99.3	98.4	127.5	9163
Significance Probability > F (log transformed data)									
Mg	0.0891	0.1155	0.8622	0.0277	0.8317	0.4535	0.4535	0.0289	0.1588
Grass	0.0241	0.0253	0.2439	0.3266	0.0115	0.0326	0.0326	0.0065	0.0503
Mg*G	0.3586	0.2593	0.9277	0.1258	0.3678	0.3804	0.3804	0.0630	0.4339
S Err	315.96	349.62	323.01	153.09	96.51	117.12	53.33	76.26	1120.3



**Figure 10.** Dry weights of biomass fractions as affected by magnesium and grass treatments, 18 months after application. At age 3.

An increase in biomass due to removal of grass competition was more strongly apparent. Total biomass increased by 33%, from 9163 kgha<sup>-1</sup> to 12374 kgha<sup>-1</sup> ( $P=0.0503$ , Table 4). Needle biomass increased by 1049 kgha<sup>-1</sup> ( $P=0.0241$ ) and branch weight increased by 1045 kgha<sup>-1</sup> ( $P=0.0253$ ) when grass was controlled. The weights of all the root fractions were improved in the

absence of grass, increasing by an average of 216 kg ha<sup>-1</sup>. There were no significant interactions of magnesium and grass treatments.

The dry weights of the various biomass fractions for the different combinations of magnesium and grass treatment are shown in Figure 10. It appeared that grass control on its own was associated with the largest plot biomass. Adding Mg without controlling the grass cover caused a depression of the tree biomass in most fractions. Addition of fertiliser with grass control was still poorer than grass control without fertiliser. This may be due to a stimulation of the grass by addition of Mg causing changes in the soil moisture regime or rooting density, or possibly due to competition of the grass for the available Mg. The latter seems unlikely given the very high rate of application.

Plots treated with magnesium fertiliser had a higher total Mg content at 9.113 kg ha<sup>-1</sup> than the control treatments at 6.9 kg ha<sup>-1</sup> ( $P=0.0950$ , Table 5). This increase was shown most strongly in the 1-2 mm diameter root fraction with an increase from 0.09 kg ha<sup>-1</sup> to 0.34 kg ha<sup>-1</sup> ( $P=0.0142$ ). The <1 mm diameter root fraction increased from 0.15 kg ha<sup>-1</sup> to 0.64 kg ha<sup>-1</sup> ( $P=0.1056$ ). Needle Mg content increased by 0.49 kg ha<sup>-1</sup> ( $P=0.2700$ ).

**Table 5.** Effect of magnesium fertiliser and grass on magnesium content of tree biomass fractions, sampled 18 months after application of treatments. Main effect means.

Treatment	Mg in Biomass Fraction, Kg ha <sup>-1</sup>								Total
	Above Ground			Below Ground					
	Needle	Branch	Stem	Stump	>5mm	2-5mm	1-2mm	<1mm	
0Mg	2.963	1.792	1.376	0.399	0.072	0.125	0.086	0.147	6.962
+Mg	3.449	1.903	1.733	0.544	0.114	0.393	0.341	0.635	9.113
-Grass	3.480	2.156	1.680	0.541	0.153	0.391	0.275	0.566	9.243
Grass	2.932	1.538	1.429	0.402	0.033	0.127	0.152	0.216	6.832
Source of variation                      Probability > F (log transformed data)									
Mg	0.2706	0.8280	0.2865	0.2817	0.5161	0.4443	0.0142	0.1056	0.0950
Grass	0.2543	0.0473	0.3877	0.6841	0.0634	0.4411	0.0181	0.1733	0.0735
Mg*G	0.3144	0.5711	0.6657	0.9629	0.6775	-	0.2242	-	0.6658
S Err	0.306	0.231	0.234	0.115	0.067	0.178	0.113	0.178	0.905

Grass control resulted in an increase in the Mg content of the trees from 6.83 kg ha<sup>-1</sup> to 9.24 kg ha<sup>-1</sup> ( $P=0.0735$ ), resulting mainly from increases in Mg contents of the 1-2 mm and >5 mm root diameter fractions and the branch components of the tree. The fine root (<1 mm diameter) fraction was also increased from 0.22 kg ha<sup>-1</sup> to 0.57 kg ha<sup>-1</sup> ( $P=0.1733$ ). In addition to analysis of the ANOVA main effects, plots of the four combinations of magnesium and grass (Figure 11) showed that the Mg fertiliser plus grass control treatment had the highest Mg content, and the zero Mg plus grass the lowest in all biomass fractions.



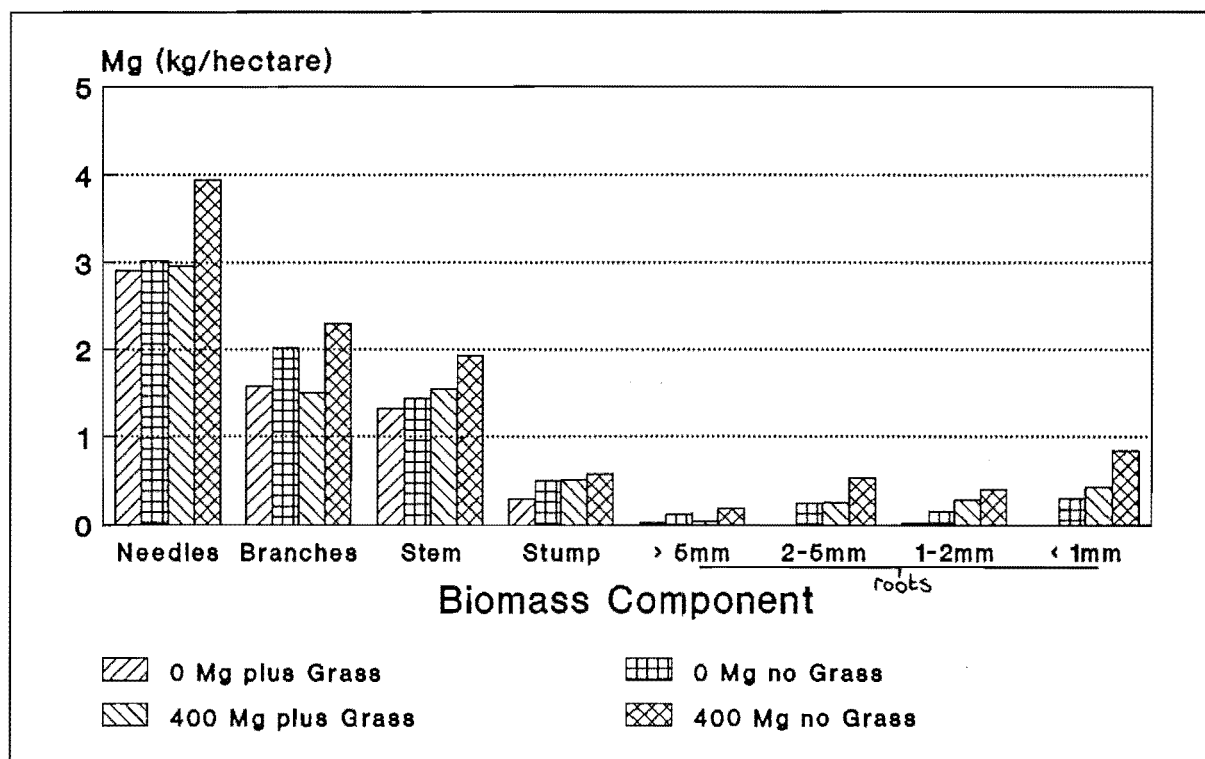


Figure 11. Magnesium contents of biomass fractions subjected to combinations of magnesium and grass treatments.

These effects of fertiliser on the biomass were unexpected. From the foliage concentrations the unfertilised trees appeared to be deficient, and trees planted on similar sites had shown strong deficiencies (Hunter 1991). A growth response was therefore thought likely when the deficiency was treated with soluble fertilisers. However, it appeared more beneficial to control the grass cover which resulted in an increase in growth. Addition of fertiliser either with or without grass control did not improve upon this treatment (Figure 10). There is a suggestion that growth was suppressed if trees were fertilised with Mg without controlling the grass cover. Grass cover had a strong effect on soil moisture (as shown in Figure 6, Chapter 3), making the site much drier in the upper horizons. A combination of this, and a growth response to applied Mg from the grass may explain the suppression. The non-significant and small increase in biomass caused by adding Mg and controlling grass over the unfertilised grassed plots suggests that Mg supply on this site was not limiting tree growth. As Mg did not appear to be limiting growth it is likely that the grass competition for moisture or Mg is the main cause of the growth limitation. This is expressed as an Mg deficiency as this is the element in shortest supply at the site and is therefore most likely to be affected.

Controlling the grass cover without adding Mg resulted in a growth increase, but no significant increase in foliage Mg content. This would suggest that the foliage Mg content is high enough to allow allocation of a portion of this pool to the extra foliage without slowing tree growth. There is however, increased Mg content in the other biomass fractions. Adding Mg and controlling grass results in an almost doubling of Mg content with only a slight increase in biomass. This is predominantly a luxury uptake of the element but may be beneficial to the tree when it is pruned, or there is a drought. The extra reserves might allow a rapid recovery from pruning shock. The extra allocation of Mg to the fine roots was interesting.

## Effect of Mg, Grass and Distance from the Trunk on Root Biomass and Length

In September 1990, one year after treatment the total tree root biomass had increased from 44 kg ha<sup>-1</sup> to 536 kg ha<sup>-1</sup>, by March 1991 it had further increased to 1271 kg ha<sup>-1</sup>. At that time percentages of the root biomass were 22, 16, 28, and 34% of the total for the < 1 mm, 1-2 mm, 2-5 mm, and > 5 mm fractions respectively. The proportions were very different however, when expressed as percentage of the total root length; with the < 1 mm fraction accounting for 76.8% of the total, and the 1-2 mm, 2-5 mm and > 5 mm fractions only 15.4, 6.2, and 1.2% respectively.

The magnesium treatment had no significant effect on root biomass and length in any of the fractions (Table 6) in either September 1990 or March 1991. The magnesium treatment also did not affect the mycorrhizal count in March 1991.

**Table 6.** Effect of magnesium, grass and distance of sampling from the trunk on root biomass, length and mycorrhizal count for all diameter classes (>5 mm, 2-5 mm, 1-2 mm <1 mm). September 1990 and March 1991. Main effects and probabilities.

Date	Treatment	kg ha <sup>-1</sup>				L <sub>v</sub>				Mycorrhizae
		>5	2-5	1-2	<1	>5	2-5	1-2	<1	
Sept 1990	0 Mg	307.2		116.5	105.5	0.0060		0.0144	0.0383	nd <sup>1</sup>
	400 Mg	269.1		131.8	141.8	0.0058		0.0156	0.0507	nd
	30cm	396.3		161.5	159.1	0.0074		0.0178	0.0553	nd
	100cm	180.0		86.9	88.2	0.0044		0.0122	0.0337	nd
Source of variation Probability > F										
	Mag	0.6745		0.7180	0.2954	0.9311		0.8254	0.3736	nd
	Dist	0.0163		0.0269	0.0390	0.0189		0.0940	0.0298	nd
Mar 1991	0 Mg	448.6	326.7	187.2	228.9	0.0012	0.0060	0.0154	0.0683	0.0585
	400 Mg	407.9	391.5	229.2	323.1	0.0014	0.0070	0.0167	0.0913	0.0561
	-Grass	622.1	507.3	232.5	328.9	0.0018	0.0095	0.0187	0.1065	0.0994
	Grass	234.4	210.9	183.8	223.1	0.0008	0.0035	0.0133	0.0531	0.0153
	30cm	715.1	484.3	224.4	290.0	0.0021	0.0082	0.0166	0.0737	0.0747
	100cm	141.4	233.9	191.9	262.0	0.0005	0.0049	0.0154	0.0859	0.0399
Source of variation Probability > F										
	Mag	0.6113	0.6434	0.6739	0.9246	0.4100	0.5619	0.6922	0.6555	0.2885
	Grass	0.2721	0.4851	0.2427	0.2805	0.2983	0.2156	0.1266	0.1925	0.0054
	Dist	0.0015	0.0012	0.3120	0.5763	0.0018	0.0210	0.6173	0.2659	0.0249

<sup>1</sup> nd = not determined

Control of grass had no significant effect on root biomass, although root lengths were increased in all root fractions, although this trend was not significant. This finding contrasts with the significant effect of grass removal on roots when the biomass analysis was done. The trends are the same here, but it is likely that the sensitivity of this analysis is less than in the former analysis as means were calculated without any form of weighting. Biomass root data was calculated using a weighting dependant on the proportion of the plot that the sample represented based on sample distance from the tree.

Root spatial distribution in the plots was uneven in September 1990, 1 year after application of treatments. There was a significant decrease ( $P = < 0.05$ ) in root biomass with distance from the trunk for all root fractions, and a similar gradient for root length ( $P = < 0.1$ ). Six months later in March 1991 the  $< 1$  mm and 1-2 mm root fractions were evenly distributed in the plot ( $P = 0.5763$  and  $P = 0.3120$ ), although there was still a gradient in the larger root diameters.

The number of mycorrhizal tips also decreased with distance from the trunk, there being 53% less, 100 cm from the trunk than at 30 cm from the trunk ( $P = 0.0249$ ). Magnesium fertiliser had no significant effect on number of mycorrhizal tips; by contrast removal of grass increased the number of tips very significantly ( $P = 0.0054$ ), from  $0.0153 \text{ cm}^{-3}$  to  $0.0994 \text{ cm}^{-3}$ .

#### **Effects of Magnesium and Distance from the Trunk on Grass Biomass and Magnesium Content**

The average grass biomass on grassed plots when it was sampled in March 1991 was  $9389 \text{ kg ha}^{-1}$ . This total comprised 54% in the foliage, 23% in the rhizomes, and 22% in the other roots. The addition of magnesium fertiliser caused the magnesium concentrations in all components to increase significantly ( $P < 0.05$ ). Foliar Mg concentration increased from 0.164% to 0.286%, Mg concentration in the rhizomes from 0.127% to 0.225%, and Mg concentration in the roots from 0.118% to 0.187%. Magnesium fertiliser did not significantly improve the dry matter weights of any of the biomass fractions ( $P = 0.3623$  to  $P = 0.8888$ ) (Table 7). However, magnesium fertiliser caused a strong increase in magnesium content in all three fractions. An increase of  $6.19 \text{ kg ha}^{-1}$  was recorded in the foliage,  $1.7 \text{ kg ha}^{-1}$  in the rhizomes, and  $1.7 \text{ kg ha}^{-1}$  in the roots. Most of the increase in content occurred in the foliage. Total Mg content increased by  $8.93 \text{ kg ha}^{-1}$  ( $P = 0.0002$ ). This was only a 2.2% recovery of the  $400 \text{ kg ha}^{-1}$  magnesium added.

The grass biomass and magnesium content was probably affected by the proximity to the tree. Although not significant ( $P = 0.1299$ ), foliage biomass was  $1300 \text{ kg ha}^{-1}$  less at 30 cm than at 100 cm from the trunk. The rhizomes and roots were not affected ( $P = 0.9358$  and  $P = 0.6201$  respectively). However, there was evidence that grass root density was lower closer to the tree stem, decreasing from  $0.900 \text{ cm cm}^{-3}$  to  $0.600 \text{ cm cm}^{-3}$  ( $P = 0.0965$ ). Total magnesium content in the grass was also lower closer to the tree ( $P = 0.0723$ ), and this was due to a  $3 \text{ kg ha}^{-1}$  difference in the foliage Mg content.



Grass Mg concentrations were strongly increased when fertiliser was applied, but grass biomass was not increased. Magnesium content in the biomass increased by 70% in the fertilised plots, but this only accounted for 2.2% of the applied Mg fertiliser. There was some indication that grass sampled at 30 cm from the tree had lower biomass and Mg content than that at 100 cm.

## Chapter 4

### II. Effect of types of Mg fertiliser and other nutrients on tree growth and foliar chemistry of juvenile *P. radiata*

#### INTRODUCTION

It was possible that the limited success of Mg fertilisers in overcoming a perceived shortage of that element may be due to a limitation of another element in addition to Mg. This section of Chapter 4 addresses that possibility, by testing the effect of a compound 'Total Fertiliser' (Nitrophoska Blue) containing all macro and micro elements necessary for tree growth. Foliar analysis of *P. radiata* planted on pumice soils has shown that boron is the other element most likely to be limiting growth (Hunter *et al.* 1991). Boron deficiency has been implicated in reduced root carbohydrate levels in trees (Atalay *et al.* 1988), and it may be that this could affect Mg uptake through a less active root system.

Calcined magnesite (MgO), as 2-5 mm chip, has been used operationally as a management treatment for Mg deficiency on pumice soils. However improvements in foliar Mg concentrations had not been measured in stands treated with this source (W. Smith *pers comm* 1989). It was not clear whether this was due to the slow solubility of this source, or if this was compounded by the presence of grass on the site. Further investigation of this observation, when confounding effects such as grass cover had been removed was required to help evaluate the usefulness of this type of Mg fertiliser.

#### OBJECTIVE

To determine whether Mg was the only element limiting *P. radiata* growth on the Halls site, and to compare the effect of calcined magnesite on foliar Mg concentrations and tree growth, with the same rate of highly soluble Epsom salts.

#### MATERIALS AND METHODS

Data from the field experiment at Halls Block are used in this section. First a subsection of treatments as outlined in the General Introduction were used to compare the Total Fertiliser, with calcined magnesite, Epsom salts and an unfertilised control. The treatments used were:

- 0 and 400 kg ha<sup>-1</sup> Mg, as MgSO<sub>4</sub>·7H<sub>2</sub>O (Epsom salts).
- 400 kg ha<sup>-1</sup> Mg, as 2-5 mm chip calcined magnesite (MgO).
- A Total Fertiliser (Nitrophoska Blue) @ 50 kg ha<sup>-1</sup> P and 120 kg ha<sup>-1</sup> N, with additional Epsom salts to raise the Mg application rate to 400 kg ha<sup>-1</sup> Mg.

There were four replicates of each treatment, and all plots were ungrassed. Nitrophoska Blue comprises N(12), P(5), K(14), S(3), Mg(1.2) plus Trace element mix. Values in parentheses are percent of total weight.

Height and collar diameter were measured in March 1990, September 1990, and March 1991. Tree volume index ( $d^2h$ ) was calculated. Current mature foliage samples were taken on all three measurement dates from two primary branches in the top third of the crown of each measured tree and bulked per plot. Analysis was carried out as outlined in Section I. Weight of 50 individual needles was recorded.

The growth data were analyzed by ANOVA, using initial height or root collar diameter as a covariate where appropriate. Nutrient concentrations and needle weights were analyzed by ANOVA. Where required, single degree of freedom contrasts between treatments were computed.

Second the full factorial experiment outlined in the Introduction (Section I) was used to test the effects of boron on tree growth and foliar nutrient concentrations and needle weight. The treatments of the full experiment were:

- 0 and 400  $\text{kg ha}^{-1}$  Mg, as  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (Epsom salts).
- Presence and absence of perennial Rye grass.
- 0 and 4  $\text{kg ha}^{-1}$  B, as  $\text{H}_3\text{BO}_3$  (Boric acid).

Magnesium and grass effects were presented in Section I of this chapter, boron effects are presented in this section.

## RESULTS

### Effects of Types of Mg and Total Fertiliser on Foliar Mg Concentration, Needle Weight and Mg Content

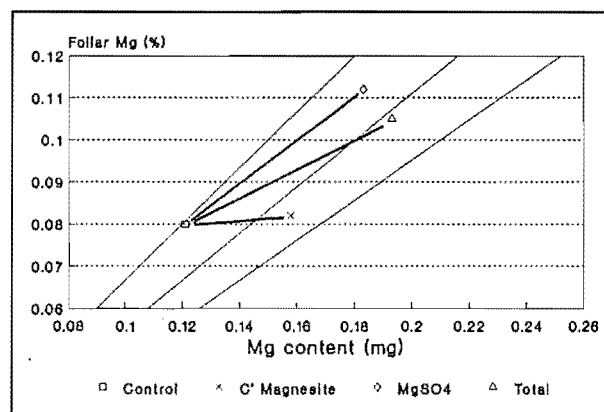
Both the  $\text{MgSO}_4$  and Total Fertiliser treatments increased foliar Mg concentrations significantly over the control at all sample times (Table 1), except for the Total Fertiliser in March 1991. The increase was greatest for the  $\text{MgSO}_4$  treatment on all three occasions ( $P < 0.05$ ). This may have been due to an antagonistic effect of the potassium on Mg uptake. The calcined magnesite treatment by contrast caused no significant improvement in Mg concentrations at any of the sampling times.

The weight of 50 needles was unaffected by treatments in March 1990, six months after fertiliser was applied ( $P = 0.3106$ ). However by September 1990 needle weights in the calcined magnesite and Total fertiliser treatments were significantly higher ( $P = 0.0145$  and  $P = 0.0457$  respectively) than the control. In March 1991 the Total Fertiliser and  $\text{MgSO}_4$  treatments had improved needle weights slightly ( $P < 0.10$ ). At all three dates, needle Mg content was significantly improved by the  $\text{MgSO}_4$  and Total fertiliser treatments ( $P < 0.05$ , except for the Total fertiliser in March 1990 when  $P = 0.1179$ ). For the calcined magnesite treatment an increase in needle Mg content was apparent in September 1990 ( $P = 0.0172$ ).

**Table 1.** Effect of calcined magnesite,  $\text{MgSO}_4$  and a total spectrum fertiliser on foliar Mg concentration (%), weight of 50 needles (g) and needle Mg content (mg).

Treatment	March 1990			September 1990			March 1991		
	Mg (%)	Weight	Content	Mg (%)	Weight	Content	Mg (%)	Weight	Content
0 Mg	0.077	1.32	1.02	0.080	1.51	1.21	0.060	1.62	0.98
C'Mag	0.074	1.45	1.07	0.082	1.93	1.58	0.058	1.80	1.04
$\text{MgSO}_4$	0.103	1.32	1.37	0.112	1.64	1.83	0.085	1.82	1.55
Total	0.093	1.28	1.19	0.105	1.83	1.93	0.069	1.82	1.25
Source of variation                      Probability > F									
Treat	0.0001	0.3106	0.0272	0.0004	0.0530	0.0010	0.0003	0.1543	0.0006
S Err	$3.7\text{E}^{-3}$	0.0627	0.075	$4.0\text{E}^{-3}$	0.0952	0.085	$3.1\text{E}^{-3}$	0.0678	0.069

Studying the results of the September 1990 sampling by vector analysis (Figure 1.) showed that the Epsom salts treatment resulted predominantly in luxury uptake (small needle weight increase, large foliar Mg concentration increase), while the Total Fertiliser caused a response in both weight and concentration. The calcined magnesite caused an increase in needle weight with an increase in uptake of Mg that maintained the  $\text{Mg}_i$  concentration. It appears that both the Total Fertiliser and the calcined magnesite treatments may result in a growth improvement while there was a less obvious response from the Epsom salts.



**Figure 1.** Vector analysis of treatment effects on foliage Mg concentration and needle Mg content, September 1990.

### Effects of Types of Mg and Total Fertiliser on Other Foliar Nutrients

Both foliar P and Al concentrations were unaffected by treatments (Table 2). Sulphur concentrations were increased slightly in March 1990 by the Epsom salts and Total fertiliser treatments, but no significant improvements were recorded thereafter for this element (Table 2). Potassium concentrations were significantly higher for the Total Fertiliser ( $P=0.0064$ ) in March 1990, due probably to the K content of the fertiliser. The foliar K concentrations in September 1990 and March 1991 tended to be higher than the control, but differences were not statistically significant. Calcium concentrations were higher in the calcined magnesite treatment than the control ( $P=0.0039$ )

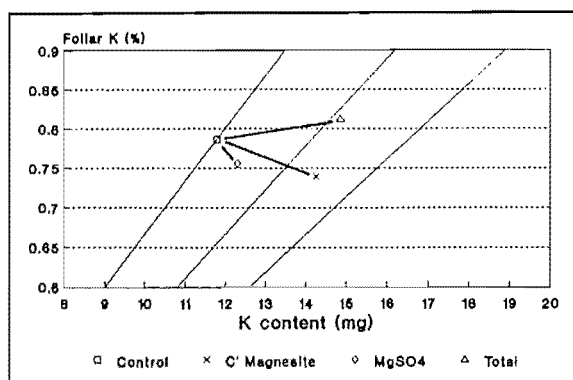


in March 1990, but were no different thereafter. Calcium concentrations were lower than the control in the  $\text{MgSO}_4$  and Total fertiliser treatments in September 1990 and March 1991 for the former treatment ( $P < 0.05$ ), and in March 1991 for the latter treatment ( $P = 0.0125$ ). It may be that there is an antagonism between Mg and Ca uptake, or that there was dilution due to additional foliage growth. Concentrations of  $\text{Ca}_t$  did not approach deficient in any of the treatments however.

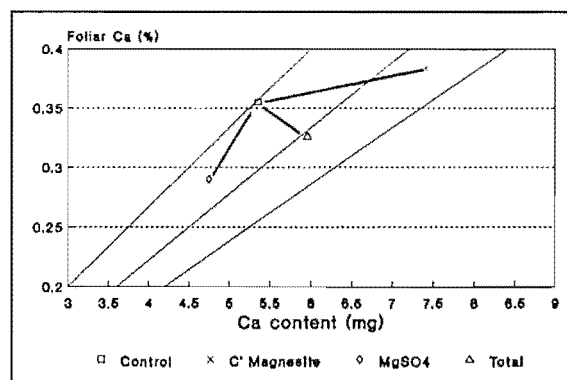
**Table 2.** Effects of treatments on foliar concentrations (%) of elements other than Mg, March 1990 to March 1991.

Sample Date	Element	Treatment				variation	
		Control	C' Mag	$\text{MgSO}_4$	Total	P > F	S E (*E <sup>-3</sup> )
March 1990	Ca	0.269	0.307	0.234	0.253	0.0001	7.5
	K	1.295	1.281	1.283	1.450	0.0093	39.0
	S	0.128	0.131	0.144	0.140	0.0006	1.9
	P	0.162	0.161	0.165	0.159	0.7529	6.3
	Al	0.015	0.014	0.012	0.012	0.2777	2.5
Sept 1991	Ca	0.355	0.384	0.290	0.326	0.0040	13.0
	K	0.786	0.739	0.756	0.812	0.2266	24.0
	S	0.123	0.122	0.128	0.127	0.5149	3.1
	P	0.139	0.136	0.138	0.136	0.9807	5.6
	Al	0.013	0.012	0.009	0.010	0.2758	1.2
March 1991	Ca	0.273	0.288	0.242	0.208	0.0001	7.35
	K	0.946	0.873	0.949	1.03	0.0675	33.0
	S	0.114	0.111	0.119	0.114	0.0849	2.1
	P	0.152	0.140	0.150	0.151	0.5280	4.1
	Al	0.027	0.023	0.024	0.023	0.5832	1.3

Vector analysis of both K and Ca supported the conclusions from the foliage concentrations and changes in needle weight. The Total Fertiliser caused an increase in foliage K content and concentration, this vector shift was interpreted as indicating a response to K (Figure 2.). This was surprising as foliar K concentrations were well above the critical concentration of 0.3% (Will 1985). The treatment effects on Ca illustrated the antagonism between Ca and Mg when  $\text{MgSO}_4$  was applied with a downwards shift of the vector (Figure 3.).



**Figure 2.** Vector analysis of treatment effects on foliar K concentration and needle K content, September 1990.



**Figure 3.** Vector analysis of treatment effects on foliar Ca concentrations and needle Ca content (mg/50 needles), September 1990.

### Effects of Treatments on Tree Growth

The three fertiliser treatments did not improve tree growth based on the variables measured at any of the measurement periods (Table 3). This lack of response contrasts with the results of the vector analysis. No biomass estimation was carried out on these plots, and it was therefore not possible to determine if the foliar biomass response indicated in the vector analysis was reflected in total biomass change.

**Table 3.** Effects of calcined magnesite,  $\text{MgSO}_4$ , and a Total spectrum fertiliser on tree height (cm), root collar diameter<sup>2</sup> ( $\text{cm}^2$ ) and volume index ( $\text{cm}^3$ ).

Treatment	March 1990			September 1990			March 1991		
	Height	d <sup>2</sup>	Volume	Height	d <sup>2</sup>	Volume	Height	d <sup>2</sup>	Volume
Control	115.9	10.60	1342	139.4	23.27	3495	270.6	52.87	14788
C' Mag	118.1	11.09	1488	140.7	23.82	3844	271.6	57.41	16184
$\text{MgSO}_4$	117.0	10.45	1434	139.7	24.52	3902	270.0	55.07	16190
Total	115.5	10.25	1393	138.4	23.84	3816	267.0	54.97	16225
Source of variation									
Probability > F									
Tmt	0.9501	0.8354	0.9688	0.9856	0.9752	0.9259	0.9788	0.7767	0.8747
S Err	3.42	0.67	162.4	4.33	1.77	457.3	7.80	3.05	1465.2

## Effect of Boron Fertiliser on Follage Chemistry and Tree Growth

Addition of boron fertiliser to the site increased the mean foliar B concentrations in March 1990 from 17 mgkg<sup>-1</sup> in the control to 45 mgkg<sup>-1</sup> in the boron fertiliser treatment ( $P=0.0001$ ). Both these values are above the critical value for boron of 12 mgkg<sup>-1</sup>. Boron had very little effect on other foliar nutrient concentrations. Boron application increased the Ca<sub>f</sub> concentration in March 1990 ( $P=0.0767$ ) and September 1990 ( $P=0.0239$ ), but not in March 1991 ( $P=0.6642$ ). In no instance was there any effect of boron on the Mg<sub>f</sub> concentration.

Tree growth was only very slightly affected by addition of boron, with a transitory 4 cm height improvement in September 1990 ( $P=0.0410$ , Table 4). Root collar diameter<sup>2</sup> and volume were not significantly affected by boron addition. Though boron has been found to be limiting growth in areas close to the trial site, it appears from these results that boron was not limiting growth on this specific site, as foliar B concentrations were well above critical and very little growth improvement was recorded.

**Table 4.** Effect of boron fertiliser on tree height (cm), root collar diameter<sup>2</sup> (cm<sup>2</sup>) and volume index (cm<sup>3</sup>). Halls Block.

Treatment	March 1990			September 1990			March 1991		
	Height	d <sup>2</sup>	Volume	Height	d <sup>2</sup>	Volume	Height	d <sup>2</sup>	Volume
0 B	116.7	9.78	1353	138.8	21.18	3409	263.2	46.52	13738
+ B	118.7	9.86	1404	142.8	21.63	3487	269.4	48.53	14320
Source of variation                      Probability > F									
Boron	0.4073	0.8736	0.6238	0.0410	0.6923	0.7676	0.1371	0.2818	0.4761
S Err	3.34	0.707	143.6	2.63	1.56	367.7	5.70	2.58	1134.8

## DISCUSSION

The low solubility 2-5 mm chip calcined magnesite had no effect on Mg<sub>f</sub> concentrations in the eighteen months following fertiliser application. But there was an increase in needle weight in September 1990, 1 year after fertiliser application. Needle weight at that time was 27% higher than in the unfertilised trees and Mg uptake had increased to maintain and slightly increase Mg<sub>f</sub> concentration. The interpretation of the vector analysis would suggest a growth response at this time, but no significant improvement in height or diameter was recorded at any of the measurement times.

The potassium in the Total fertiliser caused a depression in Mg<sub>f</sub> concentration compared to the MgSO<sub>4</sub> treatment, but the Total Fertiliser caused an improvement in needle weight of 21% over the

control, while the  $\text{MgSO}_4$  treatment resulted purely in luxury uptake of Mg. Like the calcined magnesite treatment, the improvement in needle weight was not reflected by differences in height and diameter measurement.

Calcined magnesite was less effective in increasing the Mg uptake in the tree compared to the  $\text{MgSO}_4$  treatment. This has implications for future pruning of such stands. Stands with higher  $\text{Mg}_i$  concentrations are likely to withstand the pruning shock recorded when lower crown branches are removed on magnesium deficient sites (Hunter 1991). This operation removes a large reserve of translocatable Mg from the tree. Decreased height growth, strong deficiency symptoms and even death can result. The different effect of the calcined magnesite and  $\text{MgSO}_4$  on the  $\text{Mg}_i$  concentrations will be due to the different soil reactions occurring when these fertilisers are applied. Magnesium sulphate application caused much higher soil solution ( $\text{Mg}_{ss}$ ) concentrations in the soil profile than the calcined magnesite treatment (Chapter 3). There is, therefore, a much larger pool of Mg immediately available to the tree.

No measurable growth improvement was recorded with any of the treatments applied. This suggested that no other element was limiting growth as tree growth in the Total fertiliser treatment was no different to any of the other treatments.

Based on the growth rate of the trees in the eighteen months following fertilisation, and the  $\text{Mg}_i$  concentrations, it seems that the Mg supply of the site is not limiting growth at this stage but is marginal. Increased rate of biomass production or pruning of the trees will put more pressure on the site and the trees could become magnesium limited. The  $\text{MgSO}_4$  treated trees should be less likely to become Mg limited. Whether the calcined magnesite treated trees will eventually perform better than the control trees is still unknown.

The other element suspected of being limiting on the site was boron. Foliar boron concentrations measured after 6 months showed levels to be above critical in all instances. Little or no growth response to B was measured, though  $\text{B}_i$  concentrations more than doubled in fertilised trees. Hunter (1991) showed that  $\text{B}_i$  concentrations may decline with time on Mg fertilised sites, therefore B concentrations should be monitored for several more years. It was possible that the N added in the Total Fertiliser was responsible for the increase in foliage weight. However as N was not analyzed this could not be tested.

## CONCLUSIONS

Calcined magnesite applied as 2-5 mm chip at  $400 \text{ kg ha}^{-1}$  Mg at planting did not raise  $\text{Mg}_i$  concentrations above that of unfertilised trees in the 18 months following application. But there may have been a slight improvement in needle biomass and Mg content. By contrast, the same rate of  $\text{MgSO}_4$  increased  $\text{Mg}_i$  concentrations above 0.1% within six months of fertiliser application. No improvement in tree height,  $d^2$ , or volume was measured for either of these treatments over the control trees. It appears that no other element was limiting growth on the site, as no growth improvement was recorded for any of the treatments, although the Total Fertiliser did improve needle weight and K content slightly.

## Chapter 4

### III. Effects of soil and foliage application of $\text{MgSO}_4$ fertiliser to an 8 year old magnesium deficient *P. radiata* stand

#### INTRODUCTION

The slow increase in foliar Mg concentrations and growth of Mg deficient trees following fertilisation (Hunter 1991) was puzzling. Common sense suggested that improvement should be rapid if enough Mg was added and was available to the tree.

It has been suggested that types and rates of Mg applied have not been suited to the problem in deficient trees. Dolomite, calcined magnesite and other low solubility sources such as serpentine had been tried at rates of up to  $400 \text{ kg ha}^{-1}$  Mg, and lower rates of  $25\text{-}55 \text{ kg ha}^{-1}$   $\text{MgSO}_4$  had been used. To determine whether the slow response was due to poor uptake of Mg by *P. radiata* or due to Mg availability it was decided to use  $400 \text{ kg ha}^{-1}$  Mg as highly soluble  $\text{MgSO}_4$  (Epsom salts). This would then be comparable to studies undertaken previously with less soluble fertiliser sources (Hunter 1991), and also to the Halls experiment where this rate and type of Mg fertiliser was tested in a preventative role.

If slow uptake of Mg is characteristic of *P. radiata* irrespective of fertiliser source, due to a root influx limitation for example, then another option for rapidly raising Mg concentrations is foliar application of Mg. Early work by Will (1968) had shown such a treatment to be very effective in seedlings but his results were less conclusive in mature trees. It was suggested that wetting of the foliage might have been a problem, and also mature foliage might be less able to absorb nutrients than young foliage due to build up of waxes on the surface of the needle. With recent improvements in surfactants it was decided to evaluate foliar application once more. If the foliar Mg could be quickly improved this might 'kickstart' the tree, possibly by stimulation of the root system, allowing a synergistic effect with soil applied Mg being more rapidly assimilated. A factorial combination of these two treatments was therefore planned to test this.

#### OBJECTIVE

To determine if rapid improvement in foliar Mg concentration was possible in 8 year old Mg deficient *P. radiata*, and to determine whether application as a foliar spray improved foliar Mg concentration and had a synergistic effect on Mg uptake from the soil.

#### MATERIALS AND METHODS

##### Field Sampling

A field trial was established in 8 year old *P. radiata* at Kiorenu Rd. in southern Kaingaroa Forest in September 1990. The trees were severely Mg deficient, with strong visual symptoms and

foliar Mg concentrations of below 0.06%. The trial was designed to investigate the effects of applying  $\text{MgSO}_4$  on tree growth and foliar chemistry when applied to the soil and/or foliage. Treatments were a factorial combination of:

- 400  $\text{kg ha}^{-1}$  Mg as  $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$  (Epsom salts) applied to the soil.
- 10 grams Mg per tree applied as a foliar spray (3.3%  $\text{MgSO}_4$  solution with 0.2% Pulse surfactant).

The trial was fully randomised, with three replicates. Plots were 14 m \* 14 m, with inner plots of measured trees of 11 m \* 11 m. Magnesium sulphate was applied evenly to the soil surface by hand. Foliage application was by knapsack sprayer, trees were sprayed once, the crown being thoroughly wetted but drip kept to a minimum.

At initiation of the trial, tree heights and dbh were recorded on all inner plot trees, and volume index calculated ( $\text{dbh}^2 \cdot \text{height}$ ). Mature foliage samples from the flush previous to current were taken from the standard FRI sampling position (Will 1985) on inner plot trees and bulked to give one composite sample per plot. In March 1991, six months after fertiliser application, the trial was remeasured. Foliage samples were taken of current fully expanded mature needles (i.e. the new seasons growth), and 1 year old needles.

### Chemical Analysis

Foliage samples were dried, and the weight of 50 individual needles recorded for the current foliage in March 1991. Samples were ground in a ring mill and pelleted. The samples were analyzed for Ca, Mg, K, S, P, Al, Si and Fe by X-ray fluorescence spectroscopy.

### Statistical Analysis

The trial was analyzed as a factorial experiment with three replicates in a fully randomised design. Differences in growth between treatments was analyzed using an ANCOVA, with initial height as a covariate for height growth, and initial dbh as covariate for diameter and volume growth. Treatment effects on foliage concentrations were analyzed by ANOVA. The effects of treatments on Mg, concentration, needle weight and needle Mg content was analyzed by vector analysis (Timmer and Stone 1978).

## RESULTS

### Effect of Treatments on Foliar Nutrient Concentrations, Needle Weight and Nutrient Content

At establishment of the trial, the level of deficiency was confirmed as severe from the foliar analysis data, which showed a mean foliar Mg concentration of 0.059% in the current needles. 41% of the needles in the crown were chlorotic and needles were generally sparse with few older than one year. The trees showed classic magnesium deficiency symptoms (Plate 1).



Six months after fertiliser treatments were applied the Mg<sub>i</sub> concentrations in both the current and 1 year old needles had approximately doubled on plots where MgSO<sub>4</sub> was soil applied. This indicated that high rates of a soluble Mg source could rapidly correct low foliar Mg concentrations. The addition of soil applied Mg fertiliser raised the Mg<sub>i</sub> concentration of the current needles to 0.099% which is considered healthy, while the 1 year old needles remained deficient at 0.066%. This failure to improve foliage Mg concentrations in older foliage above critical levels could be due to irreversible change in needle structure such as necrosis, keeping overall concentrations low even though parts of the needle have a sufficiency of magnesium.

In the plots where Mg was not applied to the soil the current needles had a higher concentration (0.046%) than the 1 year old needles which had a concentration of 0.033%. The concentration in the 1 year old needles had dropped from the September 1990 concentration of 0.059% to 0.033%. This indicated translocation of Mg from the old to the young foliage was occurring. The foliar spray treatment did not increase foliar Mg concentration in either ages of needles ( $P=0.3480$  and  $P=0.9092$ ).

### Vector Analysis

Needle weight was affected by soil and foliar application of Mg in combination, as illustrated by the significant interaction ( $P=0.0098$ , Table 1). The soil application caused a slight improvement in needle weight of 7%, though this was only significant at  $P=0.1886$ . Needle Mg content was improved from 0.62 mg per 50 needles to 1.44 mg per 50 needles ( $P=0.0001$ ) on plots where Mg was soil applied. A soil \* spray interaction was recorded for this variable ( $P=0.0351$ ). Study of the vector analysis plot (Figure 1.) showed the best treatment to be soil application of MgSO<sub>4</sub> without foliar spray. The foliar spray in conjunction with the soil application caused less of a rise in Mg<sub>i</sub> and a smaller change in needle Mg content (Table 1). The reason for this result is not known.



Plate 1. Typical condition of *P. radiata* trees at Kiorenu at initiation of the field trial.

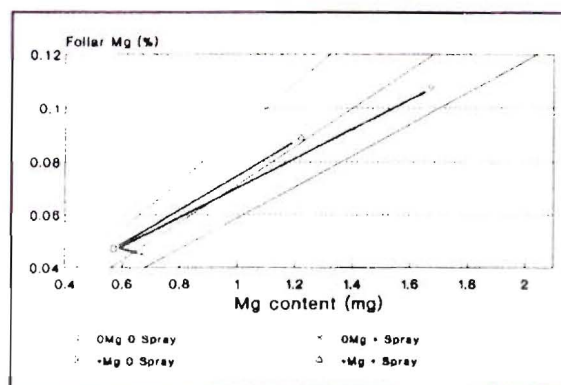


Figure 1. Effects of soil and foliar applied Mg on Mg<sub>i</sub> concentration, and Mg content of current foliage in 8 year old Mg deficient *P. radiata*.

**Table 1.** The effect of soil and foliar applied Mg on foliar concentrations (%), needle weight and Mg content in current foliage, in 8 year old trees at Kiorenu, six months after fertiliser application.

Treatment		Element concentration (%)						Weight	Content
Soil	Spray	Mg	Ca	K	P	S	Al	(g)	(mg)
0	No	0.047	0.131	0.863	0.140	0.106	0.038	1.24	0.57
0	Yes	0.045	0.148	0.785	0.145	0.104	0.037	1.49	0.67
400	No	0.108	0.232	0.847	0.152	0.138	0.036	1.55	1.67
400	Yes	0.089	0.226	0.899	0.146	0.138	0.036	1.36	1.22
Source of variation		Probability > F							
Soil		0.011	0.0121	0.4284	0.2398	0.0001	0.3968	0.1886	0.0001
Spray		0.3480	0.8521	0.8304	0.9067	0.8217	0.6948	0.6389	0.1382
Soil*Spray		0.4604	0.6846	0.3053	0.3340	0.7641	0.6948	0.0098	0.0351
S Err		0.0105	0.0276	0.0587	0.0054	0.0042	0.0024	0.064	0.106

### Effects of Treatments on Other Foliar Nutrient Concentrations

Foliar calcium concentrations in the 1 year old foliage were increased by soil application of  $\text{MgSO}_4$  from 0.272% in the control to 0.396% ( $P=0.0280$ ) in the fertilised plots, an increase was also recorded in current foliage (0.229% vs 0.139%,  $P=0.0121$ ) (Table 2). This trend was opposite to that found in juvenile trees at the Halls site where  $\text{Ca}_i$  concentrations were depressed by soil applied  $\text{MgSO}_4$ . Both the soil and foliar treatments increased  $\text{S}_i$  concentrations over the controls in both current and 1 year old needles. Foliar spray caused an increase in  $\text{P}_i$  concentrations in the 1 year old needles ( $P=0.0295$ ), and there was an interaction between the soil and spray treatments for this element ( $P=0.0526$ ). There was, however, no effect of treatments on foliar P concentrations in the current foliage. This observation has not been explained. Of the other elements, K and Al were unaffected by any of the treatments. These results are consistent with the interaction recorded in the foliage variables, where the combined treatment of soil and foliar application caused a depression of foliar Mg concentration and needle Mg content compared to the soil application alone.

### Effects of Treatments on Tree Growth

At the beginning of the experiment plot mean tree height was 6.1 m, diameter 10.4 cm and volume 66992  $\text{cm}^3$ . Mean height increment over the spring and summer was 0.86 m, dbh increased by 1.1 cm, and tree volume by 28713  $\text{cm}^3$ . There were significant interactions between the soil and spray applications for both dbh ( $P=0.0563$ ), and volume index ( $P=0.0445$ ) (Table 3). This resulted from the combined soil and foliar application causing a suppression of growth response compared to the treatment where Mg was applied to the soil alone. The reason for this is unknown.



**Table 2.** The effects of soil and foliar applied Mg on elemental concentrations (%) in 1 year old foliage, in 8 year old trees at Kiorenui, six months after fertiliser application.

Treatment		Element concentration (%)					
Soil	Spray	Mg	Ca	K	P	S	Al
0	No	0.032	0.244	0.550	0.106	0.098	0.071
0	Yes	0.035	0.300	0.591	0.131	0.110	0.073
400	No	0.061	0.416	0.654	0.114	0.138	0.064
400	Yes	0.060	0.376	0.650	0.116	0.149	0.071
Source of variation		Probability > F					
Soil		0.0101	0.0280	0.2706	0.4812	0.0002	0.2550
Spray		0.9092	0.8651	0.7941	0.0295	0.0817	0.2900
Soil*Spray		0.7801	0.3216	0.7475	0.0526	0.9767	0.4704
S Err		0.0072	0.042	0.0640	0.0047	0.0051	0.0032

**Table 3.** Effect of soil and foliar application of  $\text{MgSO}_4$  on tree height (m), dbh (cm), and volume ( $\text{cm}^3$ ) six months after treatment, March 1991. Means adjusted for initial covariate.

Treatment		Growth data		
Soil	Spray	Height	dbh	Volume
0	No	6.86	11.4	91724
0	Yes	7.03	11.6	97866
400	No	7.04	11.7	99448
400	Yes	6.91	11.5	93784
Source of variation		Probability > F		
Soil		0.7615	0.3318	0.4030
Spray		0.8855	0.6962	0.9174
Soil * Spray		0.2253	0.0563	0.0445
Std Error		0.094	0.073	2176

## DISCUSSION

This study has shown that it is possible to increase  $Mg_i$  concentrations in Mg deficient *P. radiata* within six months, by using  $400 \text{ kg ha}^{-1}$  Mg as  $MgSO_4$ . This contrasts with the slow improvement in  $Mg_i$  concentrations found by Hunter (1991) in three field experiments in Mg deficient *P. radiata*. One trial took five years before  $Mg_i$  concentrations increased significantly, the second, two years and the third showed a small increase in the first year followed by steady improvement to a plateau after three years. These trials used dolomite at rates between 20 and  $400 \text{ kg ha}^{-1}$  Mg or a combination of dolomite with  $MgSO_4$  at between 25 and  $50 \text{ kg ha}^{-1}$  Mg compared with the  $400 \text{ kg ha}^{-1}$  Mg as  $MgSO_4$  used in this experiment. This would suggest that higher rates of soluble Mg than Hunter used are required to rapidly increase  $Mg_i$  concentrations to allow a subsequent growth response.

Hunter (1991) also showed that a rapid improvement in tree growth did not occur in his experiments. This experiment showed no growth improvement, being measured only six months after fertilisation. However, in plots where  $MgSO_4$  was applied to the soil, foliar Mg concentrations were above critical at that stage and improved growth should be expected from that time onwards.

The results of the foliar spray showed that  $Mg_i$  concentration was not improved by the treatment. The application of 10 g Mg per tree was enough to make a large difference in  $Mg_i$  concentration. Calculation based on a foliage weight of 7.6 kg per tree for a tree of 6.1 m height and 10.3 cm dbh (from Hunter 1991), and using the mean  $Mg_i$  concentration of 0.059% measured at the start of this experiment computes to a content of 4.48 g Mg in the foliage. To increase the  $Mg_i$  to a healthy 0.10% would require an added 3.12 g Mg in the foliage, approximately 30% of that actually applied. There may have been a problem with absorption of Mg into the needle, or possible leaching of the applied Mg from the needle in rainfall. The fact that the sulphate anion associated with the Mg seems to have increased  $S_i$  concentrations slightly while  $Mg_i$  concentrations did not rise is unexplained.

The reasons for the interaction between foliar and soil applied treatments on both foliar weight, foliage Mg content and tree growth are not known. It is possible that the concentration of Pulse used (0.2%), while according with the manufacturers recommendations caused problems when applied to pine needles. Foliar sprays had been attempted previously with mixed success (Will 1968). Rapid improvement in tree vigour was found in nursery stock, but positive results were less clear in mature trees. Given the improvements in effectiveness of surfactants, this may be a beneficial area of research in the future (P. Stevens *pers comm* 1991).

The increase in  $Ca_i$  concentration following soil application of Mg opposed previous findings (This Chapter Section II, Hunter 1991) where  $Ca_i$  concentrations decreased following Mg fertilisation. Possibly the high rate of  $MgSO_4$  applied caused exchange of surface adsorbed  $Ca^{2+}$  into soil solution in large enough concentrations to affect uptake. Although why this should occur in this soil and not at Halls block, which probably has a higher  $Ca_e$  concentration, is not known. Furthermore it was surprising that K uptake was not altered.

## CONCLUSIONS

Foliar magnesium concentrations in Mg deficient trees can be raised above critical levels within six months if  $400 \text{ kg ha}^{-1}$  of soluble Mg is applied to the soil. Foliage application of 10 g Mg per tree was not effective in raising Mg<sub>i</sub> concentrations. Tree growth in treated plots had not improved after six months, but as the foliar concentrations were adequate, a growth response could be expected in the near future. There was a negative interaction in trees treated with both soil and foliar Mg application, and this might be due to an effect of the Pulse surfactant.

## Chapter 5

### Effects of Mg nutrition on dry matter allocation patterns in *P. radiata*

#### ROLE OF MAGNESIUM IN THE PLANT

The most familiar role of magnesium within the plant is as a component of the chlorophyll molecule. However the Mg thus linked accounts for only 5 to 10% of the total Mg within a leaf. A further 5 to 10% is contained in the chloroplast but is not part of the chlorophyll molecule. The cytoplasm may contain a further 10 to 20%. The remainder of the Mg is found in the vacuoles. The high concentration of Mg in the chloroplast and cytoplasm helps maintain a high pH, thus influencing protein structure and enzyme activity (Marschner 1986).

Magnesium ions in addition to those in the chlorophyll molecules are essential for the photosynthetic process. Carbon dioxide is assimilated by the carboxylation of Ribulose BisPhosphate (RuBP), using the energy stored by the light reaction. The enzyme RuBP carboxylase is strongly activated by the  $Mg^{2+}$  ion. Phosphoglycerate (PGA) is formed and is then further reduced to glyceraldehyde-3-phosphate (GAP). This is then synthesised to starches and sugars. At this stage another enzyme with a high  $Mg^{2+}$  requirement is involved. Fructose 1,6, diphosphate regulates assimilate partitioning between starch synthesis and triose phosphate export in the chloroplast. When magnesium is deficient, starch accumulates in the chloroplast and causes increased dry matter content of the leaves (Marschner 1986).

Magnesium is also essential for protein synthesis; it bridges between ribosome units. When  $Mg^{2+}$  levels are low the subunits dissociate and protein synthesis ceases. This can lead to an increase in non protein N in leaves. RNA synthesis is also adversely affected by low  $Mg^{2+}$  concentrations. In addition to these reactions Mg is required as a bridging component between substrate and many enzymes.

A deficiency of magnesium in plants causes:

1. Lower photosynthesis rates.
2. Lower respiration.
3. Lower protein N content.
4. A build up of starch in the leaves.
5. Impaired transport of photosynthate to the roots.

Magnesium appears therefore to be a critical component in the carbon fixation "motor" of the tree, and items 1 to 4 are likely to affect item 5. This impaired movement of photosynthate to the root system has strong significance for the nutrient uptake of the tree. Lower photosynthesis rates alone have been shown to be less important in Mg deficient Norway Spruce (*Picea Abies*) than a combination of lower photosynthesis rate and disruption of transformation processes following initial carbon fixation (Oren *et al.* 1988). Shear (1980) stated that the first sign of magnesium deficiency in fruit trees is a breakdown of the feeding-root system, and stressed the importance of maintaining an

adequate supply of Mg to the tree. This effect of Mg deficiency on the root system could have a bearing on the rate of recovery of a tree that has been deficient for some time. It is generally accepted that plants deficient in N and P put more energy into their root systems, increasing their root:shoot ratios (Linder & Rook 1984). This allows the plant to exploit a greater soil volume and improves uptake of the element in short supply. Ericsson (1991) has shown the opposite to be the case with magnesium in birch (*Betula pendula* Roth.). A decrease in the root:shoot ratio was measured when trees were grown at sub optimal levels of magnesium. This accords with the findings of Matzner *et al.* (1986) and also Marschner (1986) and Shear (1980).

Two consequences of the decrease in C allocation to the roots are likely. First the tree's root system will be smaller, allowing less Mg uptake by the tree, due both to the roots exploiting a smaller soil volume and also due to limitations on the rate of uptake caused by the smaller root surface area. Second the decreased C allocation to the roots will provide less substrate for the mycorrhizal symbiosis which is so important in pines (Bowen 1984). Decreased mycorrhizal activity will lead to a smaller volume of soil being exploited by fungal hyphae and less Mg being assimilated by the tree (Bowen 1984). Mycorrhizae are generally recognised as being most critical for P uptake given its very low rate of diffusion. However they are also likely to be important for other elements where soil concentrations are low and movement to the root is primarily by diffusion.

If the root systems of Mg deficient trees have declined, this could affect the rate of response of trees to applied fertilisers. The movement of the Mg to the root by diffusion in the soil solution would take longer as the rooting density is lower. Also, if the root's uptake capacity ( $I_{max}$ ) is exceeded there will be a limit to the uptake rate of Mg, as uptake is then a direct function of the root surface area.

## OBJECTIVE

To determine whether the effects described above occur in *P. radiata*. Three questions were asked; first, do different levels of Mg supply affected allocation of dry matter to the root system and hence the root:shoot ratio? Second, does removal of the deficiency by foliar Mg application improve the health of the tree, and specifically the root system? Finally, do deficient stands have a smaller root biomass than healthy trees of the same age and size? A combination of solution culture experiments with seedlings and field investigations were employed.

## MATERIALS AND METHODS

### Glasshouse

A pot experiment was used to test three levels of magnesium (0.2, 1.0 and 10.0 mgL<sup>-1</sup> Mg in solution) concentration on tree growth and dry matter allocation to the roots and shoots. The experiment began with 15 replicates of the three soil solution levels, in a completely randomised design. Each 4 litre pot had two *P. radiata* seedlings planted in perlite. The Mg was applied with a background of Ingestad's solution (Ingestad 1971) found optimum for birch (*Betula verrucosa* Ehrh.), with an N concentration of 100mgL<sup>-1</sup> and pH adjusted to 5.0. Seedlings were inoculated with *Suillus luteus* mycorrhizal fungus. Nutrient solutions were added to each pot so as to keep the soils of each pot at field capacity. They were flushed with fresh solution three times per week.

The experiment was carried out in a glasshouse; the mean daytime and nighttime temperatures of 26°C and 15°C respectively. Day length was 16 hours. After 95 days five replicates of each treatment were harvested. The trees were measured for height, divided into roots and shoots and root length measured using Newman's line intercept method (Bohm 1979). Plants were dried at 70°C and ground in a ring mill. Root and shoot weights were recorded and root:shoot ratio calculated. Magnesium content of the plants (total) was analyzed using acid digest and atomic absorption spectroscopy (Nicholson 1984).

Following the harvest at day 95 the remaining ten replicates for each treatment were randomly assigned to two groups. A foliage spray of 2%  $\text{MgSO}_4$  with 0.2% Pulse surfactant was applied three times per week for one month to one group to attempt to stimulate root growth. The second group was not treated with the foliar spray. Care was taken that the spray did not reach the perlite. Nutrient solution applications to the perlite continued as before. After a further 76 days all plants were harvested and processed using the same methods as the first harvest.

### Field Experimentation

Two sets of samples were collected to look at changes in dry matter allocation as a result of Mg fertilisation. The first were collected in an existing Forest Research Institute magnesium fertiliser trial (RO2002/0 in compartment 873 of Kaingaroa forest, at Kiorenu Road). Magnesium fertiliser had been applied as dolomite at 400  $\text{kg ha}^{-1}$  Mg to severely deficient trees five years previously in 1984. The trial was a randomised complete block with two replicates. The treatments were 0, 20, 55, 150 and 400  $\text{kg ha}^{-1}$  Mg as dolomite. The site was on a pumice soil which had previously been a firebreak. Hunter (1991) reported that foliar Mg concentrations had gradually increased but that there was no significant response in tree growth. The treated and untreated plots were therefore considered as healthy and unhealthy stands where all other factors, apart from Mg status, were constant. At the time of this study, in September 1990, the trees were 8 years old and the roots had occupied the entire site. A preliminary assessment indicated no effect of distance from the trunk on root density. Eight root samples of 15\*15 cm area and 20 cm depth were taken randomly from each of two control and two plots fertilised at 400  $\text{kg ha}^{-1}$  Mg. Following an initial separation of roots from the soil on site, the samples were cleaned by washing through nested 1 mm and 2 mm sieves. They were separated into three diameter fractions; <1 mm, 1-2 mm and >2 mm and root lengths for each fraction determined using Newman's line intersection technique (Bohm 1979). Mycorrhizal infection was qualitatively assessed. The samples were dried at 70°C and the dry weights recorded.

The second experiment studied was at the Halls site (see general introduction to Chapter 4 for experimental details). This was sampled in March 1991, 18 months after the main experiment was established, and the trees were then 3 years old. Root samples were taken from all plots in the 2<sup>2</sup> factorial combination of the magnesium 0 and 400  $\text{kg ha}^{-1}$  and plus and minus perennial rye grass treatments. All plots were without boron addition. In each plot four 15\*15 cm area and 20 cm depth samples were taken at random at distances of 30 and 100 cm from four trees in each plot, making a total of 8 samples per plot. Following an initial separation of roots from the soil on site, the samples were cleaned by washing through nested 1 mm and 2 mm sieves. Roots were separated into four diameter classes (<1 mm, 1-2 mm, 2-5 mm and >5 mm). Root lengths and dry weights were recorded. In addition the number of mycorrhizal tips were counted. A weighted mean for the variables was calculated for each plot based on the proportion of the plot area represented by the samples at the two distances.

Composite current years growth mature foliage samples were collected from primary branches in the top third of the crown. All inner plot trees were sampled (between 10 and 15 trees per plot). Samples were dried at 70°C, ground in a ring mill, and analyzed for Mg by X-ray fluorescence. The Mg concentrations were used to grade treatments in order of Mg deficiency. The above ground biomass (see methods, Chapter 4) was related to the biomass of the various root fractions and total roots as a measure of dry matter allocation patterns.

### Statistical Analysis

Analysis of variance and regression analysis was used when evaluating the results of the experiments.

## RESULTS

### Effect of Solution Mg Concentration on Growth and Root:shoot Ratio

The treatments strongly affected growth and magnesium status, with trees grown in 0.2 mgL<sup>-1</sup> and 1.0 mgL<sup>-1</sup> magnesium solution showing strong deficiency symptoms (Figure 1). Mean magnesium concentrations for the whole plants were 0.027%, 0.035% and 0.128% for the 0.2, 1.0 and 10.0 mgL<sup>-1</sup> treatments respectively. Trees in the 10 mgL<sup>-1</sup> treatment were healthy, while the other trees showed strong visual deficiency symptoms.

Growth and biomass data, summarised in Table 1, showed increasing height and weight with increasing Mg concentration. Treatment effects on height and weight were strongly significant ( $P=0.0001$ ). Root:shoot ratios were also affected by treatment ( $P=0.0334$ ) with the deficient trees having a lower allocation to the root system compared to the healthy trees, though the difference between the 0.2 mgL<sup>-1</sup> and the 1.0 mgL<sup>-1</sup> treatments was not significant.

Following the foliar spray treatment, the deficient trees generally showed a marked improvement in growth within 1 to 2 weeks, with a disappearance of visual deficiency symptoms (Figure 1). However some trees in the 0.2 mgL<sup>-1</sup> treatment did not respond to treatment as they had a very small percentage of live needles remaining by this stage. In addition to this, continued spraying of the foliage of the 10 mgL<sup>-1</sup> treatment caused scorching of the foliage and a suppression of growth. When the experiment was analyzed as a whole there were no overall significant effects of foliar spray on the root:shoot ratio. This was probably due to the aforementioned problems. However differences were apparent in the 1 mgL<sup>-1</sup> treatment which was unaffected by inclusion of biomass data from dead



**Figure 1.** A comparison between seedlings treated with a foliar Mg spray and untreated seedlings. Trees grown in perlite with 1 mgL<sup>-1</sup> Mg solution, all other elements in adequate supply.



trees or needle scorching. Results for this treatment alone are shown in Table 2 and a pictorial comparison in Figure 1. There are large improvements in growth, and an overall improvement in root:shoot ratio, as proportionately more of the biomass response was allocated to the root fraction.

**Table 1.** Effects of solution Mg concentration on growth, biomass, and root:shoot ratios of seedlings grown in perlite medium after 95 days.

Treatment Soln Mg mgL <sup>-1</sup>	Trait				
	Height	Top weight	Root weight	Total	Root:Shoot
	cm	grams/pot			
0.2	7.8	0.81	0.28	1.15	0.326
1.0	11.8	1.98	0.67	2.75	0.321
10.0	20.3	4.47	1.99	6.65	0.433
Source of variation Probability > F					
Mag	0.0001	0.0001	0.0001	0.0001	0.0334
Std error	0.52	0.166	0.098	0.218	0.029

**Table 2.** Effects of a 2% solution of Mg applied to foliage of seedlings grown in perlite medium with 1.0 mgL<sup>-1</sup> solution Mg concentration after 76 days.

Treatment	Trait				
	Height	Top weight	Root weight	Biomass	Root:Shoot
	cm	grams/pot			
+ Foliar Mg	29.15	23.53	6.99	30.52	0.290
0 Foliar Mg	20.58	11.49	2.29	13.79	0.194
Source of variation Probability > F					
P>F	0.0090	0.0099	0.0097	0.0092	0.0165
Std error	1.767	2.528	0.984	3.470	0.0224

#### Effect of Deficiency on Root Length and Biomass, Kiorenui Site

The data from the Kiorenui sampling (Table 3) showed that there were consistently more roots in the fertilised plots as compared to the control plots. Root length of the <1 mm fraction in the fertilised treatment was nearly double that of the control for instance. Total root length was 58% greater in the fertilised plots ( $P=0.0478$ ). Root weight followed similar trends. As the trees in these treatments differed only in foliar Mg concentration and not in height or diameter, these results indicate an improved root:shoot ratio in healthy trees. Observations of mycorrhizal activity associated with the root samples showed more mycorrhizal root tips in the healthy stand.



**Table 3.** Effect of Mg fertiliser on root length and biomass in 8 year old *P. radiata*, Kiorenu site.

Treatment	$L_v$ (cmcm <sup>-3</sup> )				kg ha <sup>-1</sup> 20cm <sup>-1</sup>			
	Root diameter class							
	<1m m	1- 2mm	>2m m	Total	<1m m	1- 2mm	>2m m	Total
Control	0.0855	0.0260	0.0086	0.1202	277.9	446.1	1063.4	1787.7
MgSO <sub>4</sub>	0.1533	0.0448	0.0103	0.2085	613.9	642.1	2195.2	3451.6
Source of variation                      Probability > F								
Mag	0.0941	0.0707	0.6048	0.0478	0.0533	0.3949	0.2020	0.1731
Std err	0.0158	0.0037	0.0019	0.0141	57.13	128.91	427.45	565.88

The results suggest a better flow of carbon to the root system and an improvement in the amount of substrate available for the mycorrhizae.

#### Effect of Varying Degree of Mg Deficiency on Root:Shoot Ratio, Halls Site

The four treatments analyzed here had different Mg<sub>i</sub> concentrations (Table 4) indicating varying degrees of Mg deficiency. The ANOVA done on the root : shoot ratio, showed there were no significant treatment effects or interactions, though the zero Mg plus grass treatment had a very low ratio. However there was only one replicate of this treatment so this estimate was less reliable than the other treatments. Furthermore a regression of Mg<sub>i</sub> concentrations against root : shoot ratio, was not significant ( $r^2 = 0.0018$ ,  $P > F 0.8912$ ) indicating no obvious relationships. It appears, therefore, that the dry matter allocation pattern is not related to degree of deficiency. Similarly no relationship was found between the number of mycorrhizal tips and treatment or degree of deficiency (Table 4).

## DISCUSSION

On Mg limited sites it has been suggested that photosynthesis and carbon transformations are adversely affected by a shortage of Mg and this decreases allocation of carbon compounds to the root system (Marschner 1986, Ericsson 1991). This shows up as poorer root growth and less mycorrhizal activity. The volume of soil exploited by the tree would therefore be smaller, so further reducing the amount of Mg available to the tree. In turn, this would decrease carbon fixation and other physiological processes. This cycle could lead to a spiral of decline, until the tree reaches a new equilibrium with the site, at a slower growth rate. In severe cases trees could stagnate and die, as has been noted at a number of sites in Kaingaroa forest (Hunter 1991). Decreasing leaf area by pruning could place the trees under even greater stress.

**Table 4.** ANOVA results of treatment effects on root : shoot ratio, foliar Mg concentrations and number of mycorrhizal root tips, Halls site, March 1991.

Treatment	Trait		
	Root : Shoot	Mg <sub>f</sub>	Mycorrhizae
		% dm	tips cm <sup>-3</sup>
- Grass 0Mg	0.1225	0.060	0.108
+ Grass 0Mg	0.0114	0.062	0.008
- Grass +Mg	0.1264	0.085	0.090
+ Grass +Mg	0.1037	0.095	0.022
Source of variation      Probability > F			
Magnesium	0.2731	0.0001	0.2885
Grass	0.1389	0.2211	0.0054
Mag*Grass	0.3115	0.3640	0.5343
Std error	0.0311	0.0031	0.014

If such a decline occurs due to a Mg deficiency, it should be possible to measure a change in allocation of photosynthate below ground where Mg is growth limiting. This was shown in the perlite medium experiment where the trees with Mg concentrations below 0.08% and strong visual deficiency symptoms, decreased their total biomass production by between 60% and 80% (Table 1) and their root : shoot ratio by approximately 25%. As root : shoot ratios were the same for both the 0.2 mgL<sup>-1</sup> and 1.0 mgL<sup>-1</sup> treatments it may be that there is an "on/off" mechanism rather than a gradual decrease in rate of C fixation and transformations. With only three treatments however it was not possible to take this hypothesis further. That the deficiency problem is primarily caused by a lack of Mg above ground, was indicated by the very rapid growth improvements (within 1-2 weeks) that were recorded when MgSO<sub>4</sub> was applied to the foliage. The root : shoot ratio also improved dramatically following foliar Mg application (Table 2) indicating that the plants allocated more photosynthate to the roots even though the concentration of Mg available in the perlite had not altered.

The very deficient 8 year old trees at the Kiorenui site showed large improvements in root biomass following fertiliser application (Table 3) and a doubling of fine root length. As above ground growth (as measured by height and dbh) was no different between fertilised and unfertilised plots (Hunter *pers comm.* 1990) this suggests an increased root : shoot ratio. It is possible this could be a reason for the reported slow response of *P. radiata* to magnesium fertiliser. In these situations trees apparently allocate photosynthate preferentially to the roots. In addition to the stimulation of the root system, mycorrhizal activity was greater in the fertilised plots, and this is probably due to an improvement in photosynthate availability to the fungi.

The results from the 3 year old trees at the Halls site were less clear. There appeared to be no relationship between root : shoot ratio or number of mycorrhizal root tips and degree of deficiency, as expressed by foliar Mg concentration. Foliar Mg concentrations were deficient (<0.08%) for about

half of the plots but this did not reflect a change in root : shoot ratio. However, none of the plots showed severe visual deficiency symptoms. The trees at Kiorenuui for instance had been severely deficient for most of their life (8 years), and had had six years to rebuild their root system after fertilisation. Differences may therefore have had time to accumulate.

## CONCLUSIONS

Magnesium deficiency affects dry matter allocation patterns in *P. radiata*, decreasing the root : shoot ratio. This was measured under glasshouse conditions where a decrease of 25% was recorded, and also in 8 year old *P. radiata* at the Kiorenuui site, where healthy trees had up to twice the root length as those of deficient trees of the same size. The same effect was not recorded in 3 year old trees at the Halls site with foliar Mg concentrations ranging from deficient (0.056%) to sufficient (0.112%). It may be that the changes are gradual and will develop with time at this site or the threshold, as suggested by the perlite experiment, had not yet been reached. Mycorrhizal activity, assessed subjectively at Kiorenuui, was higher in the fertilised plots, indicating a greater carbon pool for the fungi. However, when measured at Halls, no differences were found.

The changes in rooting density will have implications for Mg uptake by the trees. Up to 50% less soil volume would be exploited by the trees at Kiorenuui when they are suffering from a shortage of Mg. This decreases the pool of Mg and other nutrients available to the trees. The slow above ground growth response following Mg fertilisation may be because of preferential allocation of dry matter below ground to rebuild a diminished root system. The fertilised trees at Kiorenuui had up to twice the root length of the unfertilised plots after 6 years, while the above ground growth had not been significantly improved.

## Chapter 6

### Modelling the uptake of Mg by *P. radiata*

#### INTRODUCTION

I have shown in previous chapters that Mg deficiency occurs in *P. radiata* planted on pumice soils and that it is treatable with varying degrees of success with applications of Mg fertiliser. Amounts of Mg assimilated by the tree vary according to site conditions - for instance, if different sources of Mg fertiliser are used or if trees on the site are subject to competition by grass. It would be an advance if we could readily predict the effect of varying conditions on Mg uptake and this requires a greater understanding of the mechanisms involved.

For too long the relation between tree growth or health, and soil nutrient status has been a static one, with measurements of the system at fixed points in time. Frequently soil nutrient concentrations have been related to some plant tissue critical level, often in foliage. Adams (1973) followed this approach to determine soil Mg critical levels at which a Mg deficiency in the tree would occur. Hunter (1991) also attempted this but with little success. While such techniques are useful, they have shortcomings, as they take no account of the dynamics of a system. It is necessary to understand more of the process of uptake of Mg and the factors affecting this uptake. In order to do this we must apply a mechanistic rather than empirical model which will allow an understanding of processes operating and prediction of changes in uptake caused by varying one or more of the variables.

Such models have been developed and are now available on computer. They allow prediction of nutrient uptake based on biological and chemical processes. The model selected for this study was developed by Barber and co-workers (Barber & Cushman 1981, Claasen and Barber 1976, Oates and Barber 1987) for agricultural crops. It has more recently been applied to trees (Van Rees *et al.* 1990, Kelly & Barber 1990), but only to seedlings.

#### OBJECTIVE

To apply a modelling approach to Mg uptake by *P. radiata* as an aid in understanding those factors, both soil and tree, that affect uptake.

#### Background to, and Concepts Underlying, the Barber-Cushman Model

The model, which runs on micro computer has been shown to be a good predictor of nutrient uptake (Schenk & Barber 1979, Itoh & Barber 1983, Barber & Cushman 1981), though Van Rees *et al.* (1990) found the uptake of  $K^+$  to be over predicted by the model. He suggested this was due to experimental problems rather than a problem with the model itself. I will not go into the mathematics of the model here, as it has been covered in depth in various publications (Barber 1984, Barber & Cushman 1981, Claasen & Barber 1976), though I will discuss the underlying concepts of the model and relate them to the parameters required and highlight the uptake of Mg in particular.

The model only considers "available" forms of nutrients, i.e.  $Mg^{2+}$  in solution or adsorbed onto exchange sites. No account is taken of mineralisation or weathering products. The review carried out by Barber (1984) for Mg showed most of the soils he studied to be well above the concentrations of solution Mg in pumice soils in New Zealand, with less than 10% of  $Mg_{ss}$  concentrations below  $10 \text{ mgL}^{-1}$ . By contrast, pumice soils have concentrations of the order of 0.2 to  $1.0 \text{ mgL}^{-1}$  (Payn this study, Hunter 1991). Exchangeable levels are also low compared to soils reviewed by Barber, and levels are the lowest overall for New Zealand soils (Metson & Brooks 1975). Buffer power ranged from 1.2 to 61.7 (Barber 1984).

## UPTAKE OF MAGNESIUM BY TREES

### Soil supply of Mg

There are two main mechanisms for movement of Mg to the soil/root interface. Firstly, movement by mass flow, where Mg is transported to the root in water destined for transpiration. Previous studies (Oliver & Barber 1966) have shown this to be the dominant form of movement of Mg in agricultural soils. An accumulation of Ca has been recorded at the root surface where supply exceeds the plant's uptake rate; a similar phenomenon could occur with Mg. In pumice soils however, where  $Mg_{ss}$  concentrations are 10 to 100 times lower than agricultural soils, such a build up of Mg is unlikely. In this case only a small proportion of Mg required by the plant may be supplied in the transpiration stream.

The second mechanism of nutrient movement to the plant is by diffusion. In this case  $Mg^{2+}$  will move down the concentration gradient created by depletion of Mg at the root surface due to plant uptake. The rate of diffusion of an ion in water, expressed as the diffusion coefficient  $D_i$ , can be described by:

$$J = D_i A (\delta C / \delta x) \quad (1)$$

where J is the steady state diffusive flux, A is the area across which diffusive flux is measured, and  $\delta C / \delta x$  is the concentration gradient. A diffusion coefficient in a homogenous medium such as water will be higher than in a heterogenous medium such as soil. Three factors decrease the diffusion coefficient in soil :- the proportion of water in the soil volume, the tortuosity of the diffusion path through the soil pores, and the effects of the soil matrix on ion movement; (e.g. pore diameters, or adsorption chemistry). An effective diffusion coefficient ( $D_e$ ) can be calculated for a soil taking into account these factors (Nye & Tinker 1977):

$$D_e = D_i \theta f_1 \delta C_i / \delta C_s \quad (2)$$

where  $\theta$  is the volumetric moisture content,  $f_1$  is the tortuosity or impedance factor and  $\delta C_i / \delta C_s$  is the reciprocal of the buffer power of the soil. As  $\theta$  decreases and  $f_1$  increases, i.e. the diffusion path becomes longer, the value of  $D_e$  will diminish. Similarly, ions which are more strongly adsorbed by the soil will have lower  $D_e$  values. Effectively the ions have to move further to cover the same linear distance. The average linear distance moved by an ion can be calculated from:

$$\text{Distance} = (2D_e t)^{0.5} \quad (3)$$

where  $t$  is time. The volume of soil that contributes to a plants nutrient supply over a given period can be calculated from these equations.

A further component of nutrient supply to the root is actual interception of nutrients by root growth. However, this is likely to be minimal compared to the other two mechanisms when the low rooting density of pines and low soil Mg concentrations in pumice soils are considered. This was defined by Barber (1984) as the quantity of nutrient present in a volume of soil equal to the root volume. For pine with a root density of  $0.1 \text{ cm cm}^{-3}$  (Chapter 4), and root diameter of 1 mm, this would equate to less than 0.1% of the nutrients present. This is approximately 10% of the supply for Soybeans and other agricultural crops.

The importance of mass flow or diffusive components can be calculated by comparing actual nutrient uptake with predicted given the volume of water transpired and the concentration of nutrient in solution. This ratio is termed the Mass Flow Coefficient (MFC) (Prenzel 1979).

### Nutrient Uptake by Roots

One of the major roles of plant roots is in the absorbtion of ions from soil solution. The uptake mechanisms recognised are of two types; active uptake via the symplasmic pathway, where energy is required to absorb an ion against a concentration gradient, and passive uptake is via the apoplasmic pathway where ions move through the free space in the cell walls and into the endodermis. This may not require energy. Calcium moves into the root via passive uptake, while evidence for Mg uptake is of mixed opinion, with Ferguson & Clarkson (1975), Higginbotham (1967) and Shepherd & Barling (1973) suggesting passive uptake; and Leggett & Gilbert (1969) finding evidence for active uptake.

Whether an ion is taken up actively or passively the rate of uptake is governed by Michaelis-Menten type kinetics (Barber 1984, Nye & Tinker 1977). This relates to the enzyme controlled carrier molecules involved in ion transfer. The rate of ions entering the root passively is governed by the potential gradients established by active ion uptake; they therefore also exhibit Michaelis-Menten type uptake kinetics. The flux ( $I$ ) of ions into the root is determined by:

$$I = I_{\max} C_i / K_m + C_i \quad (4)$$

Where  $I_{\max}$  is the maximum flux into the root,  $C_i$  is the solution concentration and  $K_m$  is the Michaelis-Menten constant.

In addition to describing the flux of nutrient into the root, the capacity of the root must also be considered. This takes into account the actual size of the root system, the volume of soil exploited by the roots, and the surface area of the root system. Total uptake by the plant will be limited by a combination of the value of  $I_{\max}$  and the total root surface area if a limitless supply of nutrient at the root surface is assumed. For example if a plant has a low  $I_{\max}$  value compared to another type of plant, it would need to increase its total root surface area above that of its competitor if it was to assimilate the same total amount of nutrient.

## THE BARBER-CUSHMAN MODEL

The model describes the more significant processes involved in nutrient uptake by roots. It synthesises information gathered from a range of research fields in plant nutrition. Parameters used in the model include those describing supply of nutrients by the soil, nutrient uptake at the root surface, and information on root characteristics (Table 1).

**Table 1.** Parameters used as inputs in the Barber-Cushman nutrient uptake model (from Barber 1984).

Parameter	Description
$C_{ii}$	Initial soil solution conc ( $\mu\text{molcm}^{-3}$ )
$b$	Buffer power ( $C_s/C_i$ , dimensionless)
$D_e$	Effective Diffusion Coefficient ( $\text{cm}^2\text{s}^{-1}$ )
$L_0$	Initial root length (cm)
$k$	Rate of root growth ( $\text{cms}^{-1}$ )
$r_0$	Mean root radius (cm)
$r_1$	Mean half distance between root axes (cm)
$I_{\max}$	Maximum influx of nutrient into root ( $\mu\text{molcm}^{-2}\text{s}^{-1}$ )
$K_m$	Nutrient conc at $0.5 I_{\max}$ ( $\mu\text{molcm}^{-3}$ )
$C_{\min}$	Nutrient conc below which influx ceases ( $\mu\text{molcm}^{-3}$ )
$v_0$	Mean water influx into root ( $\text{cms}^{-1}$ )

### Soil Parameters

The three soil nutrient supply parameters cover the concentration of nutrients in soil solution at the start of the experiment ( $C_{ii}$ ), the buffer power ( $b$ ) which is the ratio of adsorbed ions to ions in solution, and the Effective Diffusion Coefficient ( $D_e$ ) which describes the rate of diffusion of an element under specific conditions of soil moisture and structure.

### Nutrient Uptake by Roots

Plant nutrient uptake is described by three parameters;  $I_{\max}$ , the maximum influx rate of nutrient per unit root surface area;  $K_m$ , which is the solution concentration at which  $I$  equals half  $I_{\max}$ ; and  $C_{\min}$  which is the solution concentration where influx and efflux of the nutrient at the root surface equals zero.

## Root Uptake Characteristics

The root's nutrient uptake capacity is a function of its initial surface area ( $L_0$ ), the rate of root growth, ( $K$ ), and the mean root radius ( $r_0$ ) used to calculate surface area. Half distance between root axes ( $r_1$ ) is also necessary to compute the volume of soil available to that root without competition. The final parameter is water influx rate into the root ( $\nu_0$ ), this is a function of the plant's transpiration and root surface area.

## Model Computations and Output

The model incorporates both mass flow flux and radial diffusion of a nutrient to the root. It predicts the amount of nutrient accumulated by the tree over the time of the experiment. It also calculates the concentration gradient of nutrient at the soil/root interface at the end of the simulation run. In addition the change in rate of influx of nutrient into the root is calculated with time.

## OBJECTIVES OF THE CHAPTER

To predict soil solution Mg concentrations at which all Mg would be supplied to the tree by mass flow, using published data from the Puruki catchment.

To determine mass flow coefficients based on the available data to determine the relative importance of Mg supply to the tree by mass flow and diffusion.

To apply the Barber-Cushman model to data collected at the Halls experimental site to assess the most important factors affecting Mg uptake on this site.

To evaluate how well the model predicted the actual Mg uptake by trees under varied conditions of fertility and weed competition.

These findings should assist in planning strategies for managing the Mg nutrition of *P. radiata*.

## MATERIALS AND METHODS

### Uptake of Mg by Mass Flow

Data previously published for *P. radiata* growth and Mg uptake in the Puruki experimental catchment (Beets & Pollock 1987) was used as the basis for this modelling exercise. The aim was to calculate theoretical  $Mg_{ss}$  critical levels ( $X$ ) given the assumption that all Mg was supplied to the tree by mass flow. This concentration would then be compared to actual measured  $Mg_{ss}$  concentrations ( $A$ ) from field studies within the three sub-catchments (Tahi, Rua, and Toru). A mass flow coefficient could then be determined (Prenzel 1979, Ballard & Cole 1974). This is the proportion of Mg supplied to the tree in the transpiration stream.

Annual data from a stand of *P. radiata* from age 3 to 12 years was available (Beets & Pollock 1987). Annual dry matter production (tonnes  $ha^{-1}$ ) for *P. radiata* had been calculated for three separate sub-catchments within the Puruki experimental area. Annual Mg uptake for these three sub-



catchments was estimated from the mean Mg concentration for each biomass fraction and the dry weight of that fraction. The mean Mg concentration used in the calculations for all fractions apart from the stemwood was 0.09% Mg. The stemwood Mg concentration was 0.03% Mg (Beets unpublished data). Volume of water transpired by the stand ( $W$ ,  $\text{mm yr}^{-1}$ ) for each year was estimated from the difference between rainfall input and streamflow at the base of the catchment (D. Whitehead & P. Beets *pers comm* 1991). Using the total annual uptake of Mg ( $U$ ) and the volume of water transpired, the  $\text{Mg}_{\text{ss}}$  concentration required to supply that amount was calculated for each year from:

$$(U/W \times 10^5) \times 10^6 = X \quad (5)$$

where  $W$  is converted to  $\text{litres ha}^{-1} \text{yr}^{-1}$  ( $W \times 10^5$ ), and kg converted to mg. The mass flow coefficient (MFC) is the ratio  $(A/X) \times 100$ . The larger the value the greater the percentage of Mg supplied to the tree in the transpiration stream.

### Uptake by a Combination of Mass Flow and Diffusion (Barber-Cushman Model)

The Barber-Cushman model was applied, not to predict absolute values of uptake from the field data, but to explore the effects of the different parameters on the Mg uptake of the tree. The approach was essentially a sensitivity analysis, in order to explain the trends noticed in the field data gathered from the Halls trial where trees had been subjected to varying types of fertiliser and grass competition. Parameters to be used in the model were derived from the results of soil solution concentration monitoring (Chapter 3), root growth and tree Mg uptake (Chapter 4), and from glasshouse experiments to measure root uptake characteristics.

### Derivation of Model Parameters

#### Root uptake parameters, $I_{\text{max}}$ , $K_m$ , $C_{\text{min}}$

A continuous flow nutrient solution apparatus was used to determine values for these variables. *P. radiata* seedlings were raised in perlite medium, and were inoculated with *Suillus luteus* mycorrhizal fungus. Seedlings were grown until 4 months old and then transferred to the flow system.

Four, 80 litre capacity flow systems were used for the study. These consisted of a 15 litre vessel with cover, connected to an enclosed 65 litre nutrient reservoir. Nutrient solutions were circulated by a small submersible electric pump. The covers of the 15 litre containers had 8 holes drilled to accept 100 ml pots containing the trees to be studied. The 100 ml pots had a 1.5 mm mesh on the base, and were filled with perlite. Seedlings were planted into the perlite. A range of Mg concentrations of 0.25, 0.5, 1.0, 5.0, and 10  $\text{mg L}^{-1}$  were used in a background of balanced Ingestads solution developed for *Betula verrucosa* Ehrh. (Ingestad 1971) to ensure all other elements were in adequate supply. The solution had a nitrogen concentration of 100  $\text{mg L}^{-1}$  with all other elements apart from Mg at the correct ratio.

Eight plants were transferred to each 15 litre growing vessel, the base of the 100 ml perlite filled support pots just submerged in the nutrient solution to immerse protruding roots totally. Solutions were continuously circulated from the reservoir using a small submersible electric pump.

A subsample of the seedlings, grown under the same conditions as those transferred to the flow system, was harvested to determine initial dry weight, Mg content and root length.

The experiment was run for 101 days in a glasshouse with an average day temperature of 25°C and night temperature of 15°C. Day length was artificially regulated to 16 hours.

At the conclusion of the experiment plants were removed from the apparatus, roots washed and the length measured using Newman's line intersection technique (Bohm 1979). Plant oven dry weight was recorded after drying to continuous weight at 70°C. Root and shoot samples were bulked by treatment, ground in a ring mill and then analyzed for Mg content using acid digest and Atomic Absorption spectroscopy (Nicholson 1984).

#### Calculation of influx rate of Mg into the root.

The amount of Mg absorbed per unit surface area of root per second, ( $I$ ), was calculated for each of the four Mg solution concentrations. It was calculated from the average Mg content of the seedlings in each treatment at the beginning ( $X_B$ ), and at the end of the experiment ( $X_T$ ), the initial and final root surface area ( $A_B$  and  $A_T$ ), and the time elapsed ( $T$ ). A mean root radius of 0.025cm was used in the calculation of root surface area. The equation for calculation of the uptake rate was:

$$I = ((I_T - I_B)/2)/(((A_T - A_B)/2) * T) \quad (6)$$

A linear root growth was assumed rather than exponential, as changes in root length were not measured during the uptake experiment. This uptake rate could therefore be an underestimate.

#### Calculation of $I_{max}$ , $K_m$ and $C_{min}$

The Michaelis-Menten equation was used to describe the uptake of Mg:

$$I = I_{max} C_i / K_m + C_i \quad (7)$$

To solve this equation for  $I_{max}$  and  $K_m$ , the reciprocal of the equation was used:

$$1/I = K_m C_i / I_{max} C_i \quad (8)$$

This may be rearranged and reduced to:

$$1/I = (K_m/I_{max}) (1/C_i) + 1/I_{max} \quad (9)$$

which is the Lineweaver-Burke equation (Lehninger 1970). Plotting  $1/I$  vs  $1/C_i$  yields a straight line, with slope of  $K_m/I_{max}$  and intercept of  $1/I_{max}$ .

#### Derivation of Soil Parameters

The soil solution data gathered when  $Mg_{ss}$  concentration was monitored under various treatments at the Halls experimental site was used as the basis for this modelling exercise (see

Chapter 3). The values of  $Mg_{ss}$  concentrations measured over the 548 day experimental period (Chapter 3) were used as  $C_{ii}$  values and mean values for the various treatments calculated.

Soil buffer power was calculated from data collected in the laboratory incubation of Mg fertilisers with three soils (Chapter 2). Soil solution ( $C_i$ ) Mg and exchangeable Mg ( $C_s$ ) concentrations expressed as  $mgL^{-1}$  were regressed upon each other and the soil buffer power derived from the b parameter of the regression model:

$$C_s = a + b C_i \quad (10)$$

This was done for the three Mg sources (calcined magnesite, dolomite, and  $MgSO_4$ ) at the Halls site. This would indicate variation in buffer power due to the different fertiliser treatments.

The effective diffusion coefficient ( $D_e$ ) for magnesium was estimated from published information (Barber 1984) plus calculated buffer powers for the Halls soil. It can be estimated from:

$$D_e = D_i \theta f_i / b \quad (11)$$

The diffusion coefficient of Mg in water ( $D_i$ ) is  $0.7 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$  (Barber 1984). Using Barber's data of  $f_i = 0.18$  in a silt loam at a water content ( $\theta$ ) of 0.2 and the range of b values calculated for the soil at Halls, a range of values of  $D_e$  was estimated.

## Plant Parameters

Root variables were measured and computed for both the <1 mm, and 1-2 mm root diameter class fractions. This was to allow prediction of uptake based on all roots of less than 2 mm diameter.

Initial root length ( $L_0$ ) of the <1 mm root fraction was determined from the first biomass data collected when the Halls field experiment was initiated (Chapter 4). Root growth rates were calculated from the final root lengths measured and the time elapsed. A linear rate of root growth was assumed as no detailed temporal study of root development was done.

The half distance between roots ( $r_1$ ) at the beginning of the experiment was calculated from the root sampling data using plot means of root length per volume of soil ( $L_v$ ) using the relation:

$$r_1 = 1/(\pi L_v)^{0.5} \text{ (Barber 1984)} \quad (12)$$

Rate of water influx into the root was calculated from the total water used by the trees in the Halls experiment over the 18 month period. Total transpiration was estimated to be 800 mm per annum, based on trees of a similar size grown at Puruki, approximately 20 km from the Halls site. Influx rate of water per unit root area per second was calculated from the same formula used to calculate rate of Mg uptake (Equation 6). A linear rate of root extension was assumed and the initial and final root surface areas used in the calculation.

## Sensitivity Analysis and Computer Methods

A sensitivity analysis of model variables was used to identify which parameters had the greatest influence on Mg uptake. Uptake by the <1 mm root fraction was modelled over the 18 month experimental period. The starting value of all variables (Change ratio 1, Table 2) were selected to simulate the native conditions occurring in the soil (Table 2). Buffer power was estimated from the ratio of exchangeable : solution Mg in the untreated soil.

The sensitivity analysis was done by varying each parameter in turn by between 0.25 and 4 times the start value, while keeping all others constant. The model was run for all combinations and the predicted Mg uptake computed, and the predicted uptake plotted against Change ratio. The parameters having most influence on predicted uptake have the steepest slope (Silberbush & Barber 1983). The model was run with 40 space segments and 72 time segments.

## Model Comparison with Actual Uptake

The model's predictions were tested against actual uptake of Mg measured in the biomass exercise carried out at the Halls site (Chapter 4). The predictions were compared to the results from the four treatments:

1. zero Mg plus grass cover
2. zero Mg minus grass cover
3. Mg applied as Epsom salts at 400 kg ha<sup>-1</sup> Mg plus grass
4. Mg applied as Epsom salts at 400 kg ha<sup>-1</sup> Mg minus grass

**Table 2.** Ranges of parameter values used for sensitivity analysis of Mg uptake by <1 mm root fraction. (See Table 1 for units).

Parameter	Change ratio				
	0.25	0.5	1.0	2.0	4.0
$D_e$	$5.0 \times 10^{-10}$	$1.0 \times 10^{-9}$	$2.1 \times 10^{-9}$	$4.2 \times 10^{-9}$	$8.4 \times 10^{-9}$
$b$	15	30	60	120	240
$C_{II}$	0.0057	0.0114	0.0228	0.0456	0.0912
$\nu_o$	$4.1 \times 10^{-10}$	$8.2 \times 10^{-10}$	$1.64 \times 10^{-10}$	$3.28 \times 10^{-9}$	$6.56 \times 10^{-9}$
$r_i$	3.00	6.01	12.03	24.06	48.12
$r_o$	0.0016	0.0125	0.025	0.050	0.100
$L_o$	$4.41 \times 10^{-6}$				
$k$	1	2	4	8	16
$I_{max}$	$1.41 \times 10^{-7}$	$2.82 \times 10^{-7}$	$5.65 \times 10^{-7}$	$1.13 \times 10^{-6}$	$2.26 \times 10^{-6}$
$K_m$	0.0035	0.0071	0.0143	0.0286	0.0572
$C_{min}$	$2.5 \times 10^{-5}$	$5.0 \times 10^{-5}$	$1.0 \times 10^{-4}$	$2.0 \times 10^{-4}$	$4.0 \times 10^{-4}$
Time (sec)	47347200				

For this study it was assumed that all Mg uptake occurred in the root fraction with a diameter less than 2 mm. This fraction comprised over 90% of the total root length at Halls site (Chapter 4).

Values for the parameters used in the four runs are shown in Table 3. Uptake kinetic parameters and root radius were assumed to be unchanged by treatment, but plant parameters such as root growth rate and density were varied according to results measured for the treatments. Values of  $C_{II}$  were affected by the Mg fertiliser application and the mean value of  $Mg_{ss}$  for fertilised and unfertilised treatments recorded in the leaching experiment (Chapter 3) were used. The buffer power in the unfertilised treatments was the ratio of  $C_{si}:C_{II}$  in the untreated soil. In the fertilised soil the buffer power was the mean ratio of  $C_{si}:C_{II}$  measured 365 and 548 days after fertiliser was applied (Chapter 3).

Diffusion coefficients were calculated using Equation 11, using the calculated buffer powers and  $f_i$  and  $\theta$  values of 0.18 and 0.2 respectively.

As no direct measure of tree water use was made between treatments, the estimated 800 mm of transpiration was used to calculate  $\nu_o$  for each treatment, this varying somewhat due to differences in root growth rate. The values for  $\nu_o$  were calculated from the total root surface area of all diameter classes, it being assumed that influx was constant, irrespective of root diameter.

**Table 3.** Model parameters used to predict Mg uptake on four treatments at the Halls experiment site.

Parameter	Treatment			
	zero Mg + Grass	zero Mg - Grass	plus Mg + Grass	plus Mg - Grass
$D_e$	$2.1 \times 10^{-8}$	$4.2 \times 10^{-9}$	$3.5 \times 10^{-8}$	$7.0 \times 10^{-8}$
$b$	60	60	3.6	3.6
$C_{II}$	0.185	0.185	1.399	1.399
$\nu_0$	$1.64 \times 10^{-9}$	$1.53 \times 10^{-9}$	$1.33 \times 10^{-9}$	$1.61 \times 10^{-9}$
$r_i$ (<1 mm)	12.03			
$r_i$ (1-2 mm)	31.06			
$k$ (<1 mm)	3.99	4.22	4.92	4.02
$k$ (1-2 mm)	0.71	0.65	0.86	0.78

## RESULTS AND DISCUSSION

### Uptake of Mg by Mass Flow at the Puruki Experimental Catchment

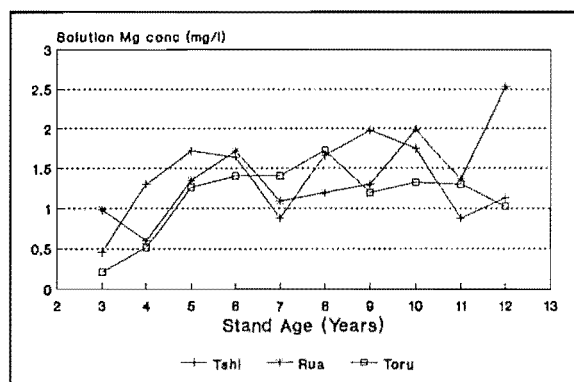
Soil solution concentrations for the three sub-catchments used in the exercise were; Tahi,  $0.3 \text{ mgL}^{-1}$ , Rua  $0.4 \text{ mgL}^{-1}$ , and Toru  $0.45 \text{ mgL}^{-1}$  (Hodgkiss unpublished data). These values were based on the solution concentrations in stream flow emanating from each of the three sub-catchments. Transpiration, estimated from the difference between rainfall input and streamflow at the base of the catchment, ranged from  $822 \text{ mm yr}^{-1}$  to  $1288 \text{ mm yr}^{-1}$  over the ten year period from age 3 to age 12. Stand age, dry matter production, estimated Mg uptake and transpiration for the three sub catchments are shown in Table 4. The mean theoretical  $Mg_{ss}$  concentrations where all Mg is supplied by mass flow, and the calculated Mass Flow Coefficients using the measured soil solution concentrations are also given in Table 4 and the data for the individual sub catchments in Figure 1 & Figure 2.

When the stands were less than 5 years old the solution concentration required to supply all Mg by Mass Flow level was lower. The rate of uptake of Mg was less than in larger trees, although the trees had a relatively high transpiration rate. A steady state was reached from about age 5 onwards when the mean solution concentration would need to be  $1\text{-}2 \text{ mgL}^{-1}$  (Figure 1). Similarly Mass Flow Coefficients plotted against tree age (Figure 2) show that a relatively greater proportion of Mg is supplied by mass flow when the trees are under 5 years old. From age 5 onwards the mass flow supplied an average 28% (range 23.7 to 34.4%) of the Mg to the tree. The remaining percentage will be supplied by diffusive transport and to a lesser extent root interception. The diffusion component of the Mg supply will be strongly affected by tree parameters such as rooting density, and soil parameters such as diffusion coefficients and buffer power.

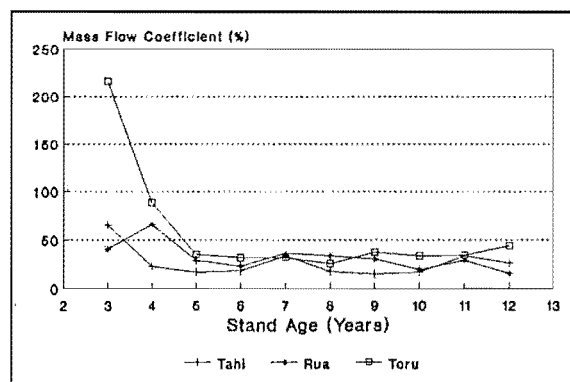
**Table 4.** Dry matter production (Beets and Pollock 1987), Mg uptake, transpiration and theoretical solution concentration required to provide 100% of Mg by mass flow, and Mass Flow Coefficients (MFC). Puruki experimental forest.

Age (years)	Dry Matter (tonnesha <sup>-1</sup> ) <sup>1</sup>	Mg Uptake (kg ha <sup>-1</sup> )	Transpiration (L*10 <sup>6</sup> ha <sup>-1</sup> )	Solution Mg (mgL <sup>-1</sup> )	MFC (%)
3	4.40	4.5	8.22	0.55	107.6
4	11.07	8.02	10.00	0.80	59.4
5	21.67	15.08	10.44	1.44	27.5
6	27.13	19.36	12.22	1.58	24.5
7	21.50	11.93	10.66	1.12	34.4
8	26.17	15.25	10.00	1.53	25.94
9	23.50	14.57	9.77	1.49	27.87
10	30.87	19.12	11.33	1.69	23.78
11	25.73	15.22	12.88	1.18	32.67
12	30.37	17.69	11.33	1.56	28.76

<sup>1</sup> Decrease represents thinning effects at ages 7, 9 and 11 years.



**Figure 1.** Theoretical solution Mg concentrations at which 100% of the tree's Mg requirement would be supplied by Mass Flow. Three sub catchments of the Puruki experimental catchment.



**Figure 2.** Mass flow coefficients (%) for Mg supply to *P. radiata* in the three sub catchments of Puruki experimental catchment.

These figures are likely to be conservative, as the exercise did not account for Mg uptake into the root biomass component, and therefore solution concentrations are likely to be higher and MFC values likely to be lower, i.e. more Mg would need to be supplied by diffusion.

Thus, in the case of rapidly growing *P. radiata*, with a relatively high Mg uptake the tree will have to rely predominantly on diffusive Mg supply, particularly after age 5. This is contrary to Barber's findings for agricultural crops on soils with much higher Mg concentrations, where the majority of Mg could be supplied by mass flow. Prenzel (1979), working with beech (*Fagus sylvatica*) with an annual uptake rate of  $3.5 \text{ kg ha}^{-1} \text{ Mg}$ , concluded that all Mg could be supplied by mass flow in a soil with a mean  $\text{Mg}_{\text{ss}}$  concentration of approximately  $0.5 \text{ mg L}^{-1}$ . Ballard and Cole (1974) working with Douglas fir (*Psuedotsuga menziesii* mirb Franco) on a well drained N deficient soil in Washington State found that 80% of Ca, an element acting similarly to Mg, was supplied by mass flow. As Mg contents in trees are normally less than Ca, it is likely in this case that all supply of Mg could be met by mass flow. It would appear that fast growing *P. radiata* planted on sites with low available Mg concentrations utilise a greater proportion of Mg supplied to the root by diffusion than slower growing species. With the greater demand for Mg, required soil solution concentrations are consequently higher and therefore the MFC lower.

The situation is likely to be worsened on a site if the topsoil is subjected to periodic drought and water and nutrient uptake is from deeper in the soil profile. Yellow brown pumice soils have much lower plant available Mg concentrations in the lower horizons compared to the topsoil. This could be one of the effects of grass competition on Mg uptake.

## Barber-Cushman Model

### Uptake Parameters

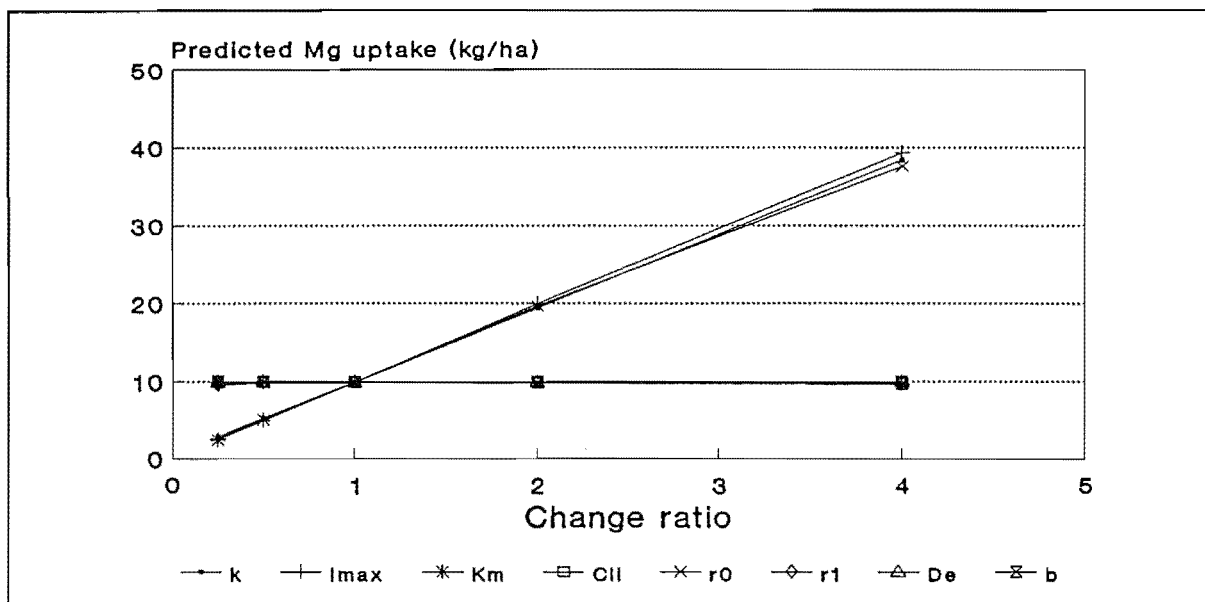
A Lineweaver-Burke plot of  $1/C_i$  vs  $1/I$  yielded values for  $I_{\text{max}}$  and  $K_m$ . The maximum influx rate was  $5.65 \times 10^{-7} \mu\text{mol cm}^{-2} \text{ s}^{-1}$ . The value for  $K_m$  was  $0.0143 \mu\text{mol cm}^{-3}$ . The minimum influx concentration  $C_{\text{min}}$  was not estimated as the concentration appeared very low for a good estimate to be made. Instead a value of  $0.0001 \mu\text{mol cm}^{-3}$ , the same as that used by Kelly and Barber (1990) for loblolly pine (*Pinus taeda* Linnaeus) was adopted. The regression model used here had an  $r^2$  value of 0.92 and was significant at  $P=0.0423$ . These uptake parameters were higher than those calculated by Kelly and Barber (1990) for loblolly pine. Their value for  $I_{\text{max}}$  ranged from  $7.90 \times 10^{-8}$  to  $1.29 \times 10^{-7} \mu\text{mol cm}^{-2} \text{ s}^{-1}$ , and  $K_m$  was  $0.0086 \mu\text{mol cm}^{-3}$ . No other comparative data are available for Mg uptake by trees, though other elements have been studied. Van Rees *et al.*, (1990) found a very much higher  $I_{\text{max}}$  for  $\text{K}^+$  uptake by loblolly pine ( $3.61 \times 10^{-6} \mu\text{mol cm}^{-2} \text{ s}^{-1}$ ). The only other published study for *P. radiata* showed a  $K_m$  of  $0.0056 \mu\text{mol cm}^{-3}$  for  $\text{NH}_4^+$  uptake (Flewelling 1979). Barber (1984) published  $I_{\text{max}}$  values for Mg uptake by wheat of  $4 \times 10^{-8} \mu\text{mol cm}^{-2} \text{ s}^{-1}$ .

### Sensitivity Analysis

It was very clear from the sensitivity analysis that predicted Mg uptake was most strongly affected by root parameters (Figure 3), with  $I_{\text{max}}$ ,  $k$  and  $r_0$  showing similar variation in predicted uptake when values were modified. Values for predicted uptake ranged from  $2.40 \text{ kg ha}^{-1}$  to  $39.31 \text{ kg ha}^{-1}$  with these parameters. The three parameters are closely related, the rate of root growth and root radius affecting root surface area and hence uptake capacity.

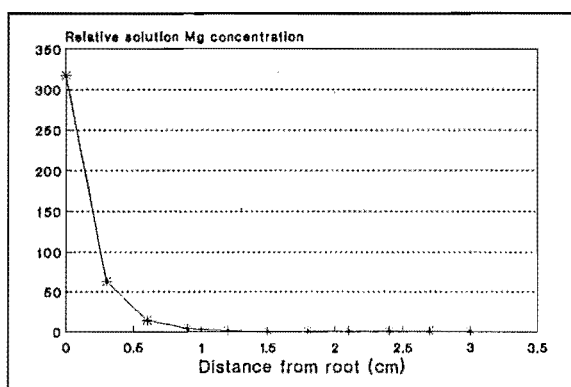
It appears that under conditions existing at the Halls site the magnesium uptake by the tree is plant limited, rather than being limited by soil Mg concentrations or rates of supply of Mg to the root.



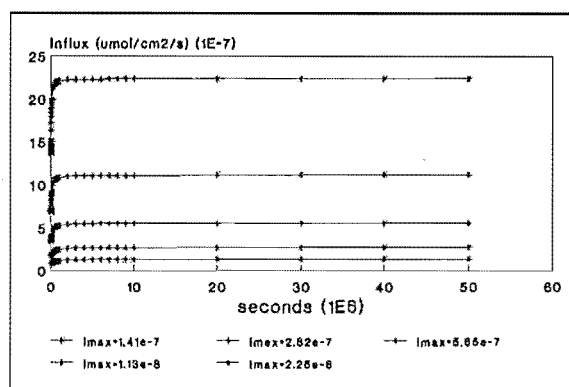


**Figure 3.** Sensitivity analysis of predicted Mg uptake into the < 1 mm diameter root fraction after 548 days, under conditions existing at Halls block.

The model calculates the concentration profile from the root surface at the termination of the model run. For soils where nutrient supply to the plant is limiting uptake, a zone of depletion develops around the root. If Mg supply to the root is adequate but the root itself is limiting uptake, then a zone of accumulation will develop. Plotting relative Mg concentration vs distance from the root for the set of values at change ratio 1 showed that an accumulation of Mg at the root was predicted by the model (Figure 4). This finding could be tested by micro analysis of Mg concentration gradients around a root.



**Figure 4.** Predicted concentration gradient of Mg from the root surface with values of model parameters from an untreated soil.



**Figure 5.** Predicted change in Mg influx into the root with time for 5 levels of  $l_{max}$ .

Uptake limitation is also illustrated by plotting influx vs time for the 5 levels of  $l_{max}$  used in the sensitivity analysis (Figure 5). In each case influx increases with time until it reaches a constant rate at the maximum influx rate. If soil supply to the root had been the factor limiting Mg uptake, a

decrease in influx to the root would be predicted with time as the depletion zone developed around the root and consequently less Mg was available for uptake.

The other root parameter in the model,  $r_1$ , or half distance between roots, had no effect on predicted Mg uptake. This suggests that inter root competition for Mg is not occurring, a reasonable assumption given the low rooting density of radiata pine trees, and hence the large volume of soil available for the individual roots to exploit.

The remaining parameters in the model had minimal influence on the predicted uptake, varying only by a maximum of  $0.29 \text{ kg ha}^{-1}$  compared to the prediction of  $9.93 \text{ kg ha}^{-1}$  at change ratio 1. This reinforces the conclusion that Mg uptake by the root was the factor most limiting uptake by the tree. For instance increasing  $C_{II}$  concentrations did not result in any predicted improvement in uptake. As the model had predicted that root influx was at a maximum level it is not possible for an increase in Mg uptake due to increased  $C_{II}$ . Buffer power and diffusion coefficient although related were treated as independent, and no differences in uptake were predicted.

#### Comparison between Predicted and Measured Mg Uptake

Uptake predicted by the Barber-Cushman model was greater than that measured in the biomass harvest for all four combinations of Mg and grass treatments (Table 5). Only the one treatment, magnesium fertiliser without grass competition was the predicted value less than twice the measured value. This over prediction could be due to an over estimation of  $I_{max}$ . Roots in the field may have a lower  $I_{max}$  as they were partly suberised, compared to the fresh young root tissue used to derive the uptake parameters in solution culture. Ferguson and Clarkson (1975) showed that Ca uptake was restricted when the endodermis of the root became suberised. This may also be the case for Mg whose uptake also follows the apoplastic pathway. Elements which are taken up via the symplasmic pathway are unaffected by root suberisation (Clarkson & Sanderson 1971, Bowen and Rovira 1970).

**Table 5.** Comparison of Mg uptake predicted by the Barber-Cushman model, and actual uptake on combinations of Mg and Grass treatments at the Halls site. Mass Flow Coefficients, theoretical  $Mg_{ss}$  for 100% mass flow supply.

Uptake ( $\text{kg ha}^{-1}$ )	Treatment			
	0 Mg plus Grass	0 Mg no Grass	400 Mg plus Grass	400 Mg no Grass
Predicted	15.14	15.35	18.68	15.93
Actual	6.13	7.78	7.52	10.69
MFC	882	695	5430	3820
$Mg_{ss}$	0.51	0.65	0.63	0.89

No other published cases of application of the Barber-Cushman model to trees could be located. It was not possible therefore to compare the accuracy of this modelling approach with other studies. The closest comparison possible was a study by van Rees *et al.* (1990). They modelled K<sup>+</sup> uptake by slash pine (*Pinus elliotii* Engelman) seedlings grown in the ground. In that instance model simulations under predicted uptake by between 0.48 and 0.83 times that observed. They suggested this under prediction to be due to the unquantified effect of fungal hyphae on K<sup>+</sup> uptake and concluded that soil processes controlling K<sup>+</sup> concentration were limiting uptake. At the Halls study site it appears that the root system rather than the soil supply is limiting uptake of Mg.

The sensitivity analysis identified  $I_{max}$ , and root growth parameters as most important in this system.

#### Calculation of Supply of Mg by Mass Flow, Halls Experiment

Assuming a transpiration rate of 800 mm yr<sup>-1</sup> in all treatments, the mass flow coefficients and theoretical Mg<sub>ss</sub> critical levels were calculated for the Halls treatments using measured Mg uptake and field Mg<sub>ss</sub> concentrations (Table 5). These were calculated as for the Puruki data, using Equation 5. Values for the MFC of greater than 100 mean more Mg was supplied to the root than was actually assimilated by the plant, leading to an accumulation of Mg around the root as suggested by the sensitivity analysis. In all cases the MFC was above 100. In the unfertilised treatments it was between 695 and 882, for the fertilised treatments it was much higher at between 3820 and 5430. The theoretical Mg<sub>ss</sub> concentration at which 100% of the Mg would be supplied by mass flow ranged from 0.51 to 0.89 mg L<sup>-1</sup>; much lower than the 4.5 mg L<sup>-1</sup> in the unfertilised and 34 mg L<sup>-1</sup> in the fertilised treatments. This range of concentrations are similar to those calculated for trees of the same age (3 years) at Puruki (Table 4). These results suggest that it is the Mg influx rate into the root that is limiting Mg uptake rather than a problem with soil supply.

If the maximum influx of Mg was limiting Mg uptake, there would be no difference in Mg uptake between fertilised and unfertilised treatments, as influx would be at the same rate for both. However, the fertilised treatments did assimilate more Mg (Chapter 4). As soil solution concentrations in the fertilised treatments were much higher than in the unfertilised treatments it is possible that the uptake of Mg into the root is proceeding by a Type II uptake mechanism rather than a Type I (Hodges 1973). Generally the Type I mechanism operates at between zero and 1 mMol (24.3 mg L<sup>-1</sup>) and has a certain value for  $I_{max}$ . At concentrations above 1 mMol the Type II mechanism has been shown to operate. This gives rise to a different and higher value of  $I_{max}$ . Soil solution Mg concentrations recorded in forest soils derived from pumice are generally below 1 mg L<sup>-1</sup> (Hunter 1991, Hodgkiss unpublished data), although the Mg<sub>ss</sub> concentrations recorded at Halls were above this at 4.5 mg L<sup>-1</sup>. The fertilised treatments' Mg<sub>ss</sub> concentrations were above the 1 mMol level, with mean concentrations over the experimental period at the Halls site of 34 mg L<sup>-1</sup>, with peaks of over 100 mg L<sup>-1</sup>.

## CONCLUSIONS

Calculated theoretical Mg<sub>ss</sub> concentrations at which all Mg is supplied to the tree by Mass Flow were between 0.51 and 0.89 mg L<sup>-1</sup> in three year old trees at both the Halls site and at Puruki Experimental Catchment. The mean concentration for trees over 5 years of age at Puruki was 1-2 mg L<sup>-1</sup>. A mean Mass Flow Coefficient of 28% was calculated for trees over 5 years old, as solution

concentrations in the stands were below the range of 1-2 mgL<sup>-1</sup>. This indicated diffusive movement of Mg to the tree to be the dominant transport process. In the younger trees under 5 years of age MFCs increased with decreasing age, indicating mass flow could supply an increasing proportion of the tree's Mg requirement. Three year old trees at both Puruki and Halls would receive all their Mg supply by mass flow.

A sensitivity analysis using the Barber-Cushman model indicated that root parameters were affecting predicted Mg uptake most strongly at the Halls site. Namely maximum influx rate ( $I_{\max}$ ), rate of root growth ( $k$ ), and root radius ( $r_o$ ). Changing soil parameters such as initial solution concentration ( $C_o$ ), buffer power ( $b$ ), or effective diffusion coefficient ( $D_e$ ) had no effect on predicted Mg uptake. This observation provides a possible explanation for the noted slow response of *P. radiata* to applied Mg. If the root system is limiting uptake and influx is running at near maximum, the increasing available Mg in the soil will have no effect until one of the tree parameters is modified, e.g. root growth rate increases. No comparative sensitivity could be done on an older stand as no data was available, however from the calculation of Mass Flow Coefficients at Puruki it is likely that soil supply parameters would be more important in Mg uptake than in the younger stand.

The Barber-Cushman model over predicted uptake by between 1.4 and 2.4 times the measured uptake in 3 year old *P. radiata*. It was suggested that this over prediction could be due to lower influx rates into roots in the field situation compared to the unsubsided roots used to measure influx in solution culture.

To improve the Mg nutrition of *P. radiata* on pumice soils it would be profitable to concentrate on factors affecting root growth rates and the kinetics of Mg influx into the root in young trees, however in older trees it may be more appropriate to concentrate on soil supply parameters such as diffusion coefficients and buffer power.

## Chapter 7

### Managing the Mg Nutrition of *P. radiata* Planted on Pumice Soils

#### INTRODUCTION

To reiterate the problems addressed in this thesis:

*Mg deficiency occurs in P. radiata planted on yellow-brown pumice soils, and the deficiency appears more severe on sites previously used for pasture production. When Mg fertiliser was added to deficient trees an increase in foliar Mg concentrations and growth were slow to occur.*

The problems were addressed through 8 research objectives:

1. To determine the reactions of magnesium applied to pumice soils.
2. To determine residence time of fertiliser Mg in the soil profile.
3. To determine how quickly magnesium can be assimilated by young and old trees when fertiliser is applied.
4. To assess the impact of grass competition on tree growth and Mg uptake.✓
5. To determine what effect Mg deficiency has on tree growth and dry matter allocation.
6. To determine what effect other nutrients have on magnesium nutrition of radiata pine.
7. To fit findings into a nutrient uptake model to aid overall understanding of the system.
8. To evaluate the research programme and assess the implications for managing the Mg nutrition of *P. radiata* on pumice soils.

#### OBJECTIVE

To summarise the findings of this research program and draw conclusions and construct a set of rules for managing Mg nutrition of *P. radiata* planted on pumice soils.

## DISCUSSION

The pumice soils studied had very low natural concentrations of both readily available (solution and exchangeable Mg), and acid extractable reserves of Mg compared to other Soil Groups in New Zealand (Metson & Gibson 1977). Topsoil concentrations fell within the range of 0-1 meq100g<sup>-1</sup> for critical levels summarised for a variety of crops (Metson 1974). The concentration of Mg in soils with a history of pasture production was no different to those found in soils solely used for forestry. The increased severity of deficiency on ex pasture sites was therefore likely to be due to some factor other than soil Mg concentrations.

Addition of Mg at rates of between 100 and 400 kg ha<sup>-1</sup> as Epsom salts, dolomite and calcined magnesite to three soils, raised exchangeable Mg concentrations to well above the 1 meq100g<sup>-1</sup> threshold below which plants may be deficient. The three fertilisers had a varied effect on soil solution Mg concentrations. Epsom salts raised solution concentrations approximately ten times the increase due to dolomite or calcined magnesite. This different equilibrium between soil solution and exchangeable Mg, if maintained in the field, has implications for the rate of response of a tree to applied Mg. The more Mg in solution the greater the proportion of the Mg assimilated by the tree that is supplied by mass flow rather than the slower rates of soil diffusion. Acid extractable reserves were improved, but by a lesser amount than the improvement in available Mg. Thus a hypothesised fixation of Mg by the pumice soils, which have a variable charge, was found to be unimportant.

These reactions were found under ideal mixing and soil moisture conditions, and suggested that rates of between 100 and 400 kg ha<sup>-1</sup> Mg should improve soil Mg levels into a range adequate for plant growth. A slow response of the tree to such additions might therefore be due to less than ideal conditions, such as rate of reaction of the fertiliser with the soil, or dry conditions affecting transport processes within the soil, or possibly rapid leaching losses of applied Mg from the soil.

Field reaction and leaching of 400 kg ha<sup>-1</sup> Mg as Epsom salts and calcined magnesite were monitored over an 18 month period. The differences in the equilibrium between solution and exchangeable Mg were similar to those found in the laboratory studies. A very rapid and large increase in soil solution Mg was characteristic of the Epsom salts treatments, and the increase above natural levels was sustained for up to 300 days. Calcined magnesite by contrast caused only a very small improvement in solution Mg concentrations. Exchangeable Mg concentrations were rapidly raised in the Epsom salts treatments, and more slowly increased by the calcined magnesite. However, after 18 months concentrations in the top 20 cm of the soil profile were well above the 1 meq100g<sup>-1</sup> level for both types of fertiliser, notwithstanding the large leaching losses from the Epsom salts treatment.

If trees failed to respond to these treatments, the problem would probably be due to either the tree's inability to assimilate Mg into the root system, or a problem with rate of transport of Mg to the root system. This is likely to affect the calcined magnesite treatment most as the solution Mg concentration was not greatly increased and therefore the tree would depend more on diffusive supply.

The fertiliser trials carried out at Halls (0-3 year old trees) and Kiorenu (8 year old trees), showed that rapid improvement in foliar Mg concentrations was possible at both sites within 6 months of application of 400 kg ha<sup>-1</sup> Mg as Epsom salts. Concentrations were doubled at Kiorenu, and almost doubled at Halls compared to controls. In both trials foliar concentrations were improved well above the critical value of 0.07%, and this improvement was sustained for the 18 months of the trial period at Halls.

No growth responses were recorded at either trial. The Halls site was only marginally deficient. In the fertilised plots the additional Mg assimilated by the tree was luxury uptake. This boosted the tree's reserves and would be important in minimising pruning shock, caused when a large proportion of Mg is removed with the lower branches (Hunter 1991). A growth response seemed likely at Kiorenui, as the trees were strongly deficient, and the measurements were made after only six months.

Work in the glasshouse and at Kiorenui showed that dry matter allocation to roots was decreased when trees were deficient, and that a below ground growth response was recorded before improvement in above ground growth parameters at Kiorenui. Thus a further explanation for the previously noted slow response of trees to Mg fertiliser, was that root systems had declined and required regeneration. In addition, the smaller root biomass would exploit a smaller volume of soil, and if a fertiliser was used that did not increase soil solution Mg by enough to supply most of the tree's requirement by mass flow, then the amount of Mg accessible to the tree would be dependent on the soil Mg diffusion rates. These could be strongly depressed by dry conditions in the soil caused by drought or grass induced low moisture conditions.

No other nutrients were limiting growth when tested at Halls although there was an indication that a total spectrum fertiliser caused a small response in needle biomass above that found with Mg alone. Mg and boron deficiencies often occur together on pumice soils which are classified as medium risk of deficiency for both these elements (Hunter *et al.* 1991).

Of the treatments applied at Halls (magnesium, grass and boron) by far the most significant was the grass. Grass control resulted in approximately 30% more tree biomass at age 3, 18 months after treatments were applied. The Mg concentrations in the trees with grass control were maintained, indicating that the Mg supply was not limiting growth.

There was an indication that application of fertiliser without grass control depressed tree growth. This was probably due to increased vigour of the grass and consequently drier soil conditions making nutrient assimilation for the tree harder. The effect was unlikely to be due to competition directly for Mg, as the recovery in the grass was only 2.2% of the total added. These findings indicate that fertilisation should be done in conjunction with weed control on such marginal Mg sites if the benefit from Mg is to be gained. On this specific site, where Mg was not limiting, grass control alone would be the best option. However if trees were to be pruned the reserves would need to be boosted by an application of Epsom salts.

The Barber-Cushman nutrient uptake model (Oates & Barber 1987) was used to do a sensitivity analysis on parameters affecting Mg uptake at Halls, and showed root growth and Mg influx parameters to be most important. As Halls was only marginally limited by Mg this result suggested that the trees would be assimilating Mg at near maximum uptake rate and that any change in root uptake capacity would affect the amount assimilated. A zone of Mg accumulation around the root was predicted for these conditions.

Calculation of mass flow coefficients for the Halls site indicated that substantially more Mg would be transported to the root surface than would be transported into the root. When comparing predicted with actual Mg uptake of Mg the Barber-Cushman model consistently over predicted Mg uptake and this may have been due to lower values of influx rates of roots in the field compared to those in solution that the influx parameters were derived from. Roots in the field will be more suberised than those in solution where all root tissue was young.

If it can be assumed that no Mg deficiency will occur if all Mg is supplied by mass flow, then soil solution critical values for adequate Mg nutrition of *P. radiata* at Halls were calculated to be approximately  $0.9 \text{ mgL}^{-1}$  for a plot with foliar Mg concentrations over 0.1% when trees were three years old. Such a critical level is a potential management tool for identification of deficient sites.

The Barber-Cushman model could not be applied to older trees as the detailed information necessary was not available. However, an analysis of mass flow coefficients was done for an age range of trees sampled at Puruki experimental catchment (Beets & Pollock 1987, P. Beets unpublished data). As the trees aged the proportion of Mg supplied by diffusion increased to approximately 75% by age 5. Once trees reach this age, it is likely that the factors most affecting Mg uptake will be soil rather than plant related. If soil solution concentrations remain low, then the rate of diffusion of Mg and the effect of variations in soil moisture on this factor are likely to assume greater importance.

For trees older than 5 years a soil solution critical level of  $1\text{--}2 \text{ mgL}^{-1}$  would be required to supply all Mg by mass flow. This is a substantially greater concentration than that found in severely deficient stands (Hunter 1991). This parameter should be tested over a range of sites with varying degree of Mg deficiency.

Mass flow and diffusion cannot be separated in the real situation however (Nye & Tinker 1977). To be able to more sensitively predict deficiency and possibly calculate Mg fertiliser application rates a more complex approach than a single critical level may be required. As Mg diffusion is affected by soil moisture conditions a determination of the variation of effective diffusion coefficients ( $D_e$ ) with varying soil moisture conditions would be required. This would allow calculation of the zone of exploitation of a root over a given time under different moisture conditions (Equation 3, Chapter 6). Estimates of root length or turnover for an age range of *P. radiata* calculations of soil volumes accessible to the tree by diffusive flux over a year could be calculated. From this and information on soil solution and exchangeable Mg concentrations and tree water use, the Mg uptake could be predicted. This value could then be compared to that for a healthy tree (from Puruki data or the survey by Madgwick *et al.* 1977). If a deficit was predicted the required addition of Mg to raise the soil concentrations in the volume of soil accessible to the tree could be calculated, and the Mg applied as a fertiliser addition. As it seems that response rates have been limited by the diffusive movement of Mg through the soil, and that the heavy applications of soluble Mg necessary to supply enough Mg in solution are expensive, these calculations could be done at establishment and the stand treated so as to prevent the deficiency occurring.

The information in this thesis, and information published previously by Hunter and Will and referred to in this thesis was collated and summarised. A set of rules were derived as an aid to management decision making. The output will be either as a field book or a computer based expert system. The rules were assigned to four categories:

1. Diagnosis of deficiency.
2. Effect of deficiency on the tree.
3. Site effects.
4. Treatment of the deficiency.

The rules are listed in Appendix 1. They are a first approximation, and will be refined and expanded further in later phases of this research.



## RESEARCH DIRECTIONS

This study was unable to delve very deeply into the soil parameters affecting Mg supply and transport, and this area of research will need to be addressed in the future. Of necessity effective diffusion coefficients ( $D_e$ ) were estimated from literature data (Barber 1984) these values should be measured for pumice soils. The variation of  $D_e$  values with soil moisture will also be necessary for modelling uptake in systems where for instance grass competition has caused soils to be drier.

As soil solution concentrations have been suggested as a management tool for identification of deficient sites these concentrations should be surveyed in the field and correlated to level of deficiency. This could be done in conjunction with the diffusion work.

It was suggested that  $I_{max}$  values may be less in field conditions than in solution based systems. Field measurement of such rates would allow testing of this. This could also be linked to testing of the model predictions of zones of accumulation of Mg around roots in young trees on pasture sites.

Information gained from these topics would allow progress to be made with application of the modelling approach, and the definition of further rules for incorporation in the expert system. This would in turn lead to more dynamic management of the Mg nutrition of *P. radiata*.

## FINAL CONCLUSIONS

Magnesium deficient *P. radiata* can be treated successfully with high rates of Epsom salts (400 kg ha<sup>-1</sup> Mg). A rapid increase in foliar concentrations is possible, and subsequent growth response likely, although some delay in above ground response may still occur due to the need to rebuild the root system. As such treatment is expensive, a preventative treatment applied at or near planting, such as 100 kg ha<sup>-1</sup> Mg as dolomite (Hunter 1991) or calcined magnesite, to sites likely to be deficient is to be preferred.

The increased severity of Mg deficiency on ex-pasture sites appears to be due to the effects of grass on soil moisture, rather than a direct competition for Mg. The sites themselves have soil Mg concentrations no lower than sites with a history of forest use only. If trees on such sites are deficient they can be treated with Mg fertilisers, but if the grass is not controlled the treatment may have a negative effect on the trees.

The predominant mode of movement of Mg to the root in trees older than 5 years was found to be by diffusion where soil solution Mg concentrations were at native levels. Trees of less than five years old were supplied more by mass flow. Soil moisture fluctuation was suggested to have a strong effect on diffusive movement of Mg and to explain the effect of grass competition on Mg uptake.

There was less allocation of dry matter to root systems in Mg deficient trees, and the first part of the tree to respond with increased growth to Mg fertiliser was the root system hence explaining the noted slow response in growth of Mg deficient trees.

A soil solution critical level of 1-2 mgL<sup>-1</sup> was suggested for screening possible deficient sites, although this would need to be tested. Further work involving validation of the modelling approach and an intensive study on soil diffusion rates under varying moisture conditions should allow the dynamic approach to the Mg testing to be expanded in conjunction with more information on *P. radiata* root dynamics.

## Appendix 1

### Rules for Managing Mg Nutrition of *P. radiata* Planted on Yellow Brown Pumice Soils

These rules will be developed further in the future. Some measure of relative importance or weighting will be required when building the rules into an expert system. At this stage the most important rules for managing the Mg nutrition of *P. radiata* are indicated by the addition of a star (\*)

#### Diagnostics

- If* Mg deficiency is suspected *Then* assess the tree for visual symptoms. \*
- If* Mg deficiency is suspected *Then* analyze needle Mg concentrations. \*
- If* Mg<sub>t</sub> concentrations are below 0.07% *Then* the tree is deficient. \*
- If* Mg<sub>t</sub> concentrations are below 0.05% *Then* the tree is severely deficient. \*
- If* Mg<sub>t</sub> concentrations above 0.1% *Then* the tree is not deficient. \*
- If* there is a dry spring *Then* Mg deficiency symptoms will be more apparent in the foliage.
- If* trees are over 10 years old and upper mid crown is sparse *Then* Mg deficiency is likely.
- If* only current needles remain on the tree *Then* Mg deficiency is a possible cause.
- If* Mg deficiency occurs *Then* it will be because the soil cannot supply the tree at a fast enough rate.
- If* all needles in a fascicle grade evenly from necrotic/bronze, through chlorotic, to green at the base of the needle *Then* Mg deficiency is likely. \*
- If* older needles show yellowing rather than younger *Then* Mg deficiency is likely. \*
- If* when viewing branch and needles end on there appears to be a golden halo round an inner green core *Then* Mg deficiency will be present. \*
- If* Mg deficiency is present *Then* it will be more pronounced in older needles. \*
- If* clone 450 of *P. radiata* is planted *Then* Mg deficiency is guaranteed.

## Effects of Mg Deficiency on the Tree

**If** Trees are Mg deficient **Then** the allocation of dry matter to the root system will decline.

**If** potassium or ammonium is applied in conjunction with Mg **Then** Mg<sub>t</sub> concentration will be lower than if Mg applied alone.

**If** trees that are Mg deficient or marginal for Mg are pruned **Then** the Mg deficiency will be worsened and the trees will lose height growth and possibly die. \*

**If** trees are thinned **Then** this will not affect the severity of Mg deficiency.

**If** Mg deficiency identified in older trees **Then** it will be the larger trees that are most affected.

**If** trees are deficient **Then** root system rebuilding is needed before above ground growth improves.

## Site Effects

**If** topsoil has been disturbed or removed **Then** the likelihood and potential severity of Mg deficiency is much greater.

**If** Grass is present with *P. radiata* **Then** this will cause drier soil conditions in the topsoil.

**If** Grass is totally eradicated on an ex farm site planted with *P. radiata* **Then** biomass will improve by approximately 30% at age 3.

**If** *P. radiata* is planted on Yellow Brown Pumice soils **Then** there is a strong likelihood of an Mg deficiency occurring.

**If** *P. radiata* is planted on YBP soils **Then** there are very low reserves of available Mg in the subsoil.

**If** the tree can exploit a buried topsoil **Then** the deficiency may be overcome as the tree ages.

**If** YBP soils are acidified **Then** soil solution Mg concentrations will increase.

**If** trees are planted on high fertility high N sites **Then** root allocation may be less than on less fertile sites.

**If** trees are planted on high fertility high N sites **Then** there is more likelihood of an Mg deficiency.

**If** grass is heavily grazed **Then** this could increase severity of Mg deficiency.

**If** spring is wet **Then** soil supply of Mg to the tree will be greater.

**If** trees planted in grassed site **Then** deficiency symptoms can occur from age 1.

**If** trees planted on ungrassed forest site **Then** deficiency will start to show clearly from age 5.

**If** trees are planted in the southern end of Kaingaroa forest **Then** the likelihood of deficiency is very high.

**If** trees are unfertilised **Then** there may be an undersupply of Mg from the soil during the spring growth flush.

**If** trees are over 5 years old and on unfertilised soils **Then** most of the Mg supply to the root will be by diffusion.

**If** trees are under 5 years old on either fertilised or unfertilised sites **Then** most Mg supply will be by mass flow.

**If** soil solution Mg <2 mgL<sup>-1</sup> and trees are over 5 years old **Then** not all Mg will be supplied by mass flow.

### Treatment of Mg Deficiency

**If** Mg fertiliser is applied at time of planting at 100 kg ha<sup>-1</sup> Mg **Then** a deficiency will be prevented. \*

**If** Mg fertiliser is applied and grass is not controlled **Then** a suppression of growth may occur. \*

**If** a low solubility Mg fertiliser is applied to deficient trees **Then** an improvement in foliar Mg conc and growth will be slow to occur (3-5 years). \*

**If** Mg fertiliser is added to deficient trees **Then** the root systems will be the first biomass component to increase in mass. \*

**If** Mg deficient seedlings' foliage is sprayed with Mg **Then** the dry matter allocation to the root system increases.

**If** Grass is sprayed out on an ex farm site **Then** approximately 10 kg ha<sup>-1</sup> Mg will become available through plant decomposition.

**If** *P. radiata* and grass are planted together **Then** they will compete for Mg in the same volume of soil.

**If** calcined magnesite is applied @ 400 kg ha<sup>-1</sup> Mg at planting on a pasture site **Then** Mg<sub>i</sub> concentrations remain marginal **But** needle mass increases by approx 20%. \*

**If** soluble Mg fertiliser applied and grass eradicated at planting on a pasture site **Then** no growth improvement will occur **But** luxury uptake of Mg will build tree Mg reserves. \*

**If** Mg applied @400 kg ha<sup>-1</sup> Mg as epsom salts to severely deficient trees **Then** Mg<sub>i</sub> concentrations will increase above critical within 6 months. \*

**If** Mg applied @400 kg ha<sup>-1</sup> Mg as epsom salts to severely deficient trees **Then** above ground growth will not improve within 6 months. \*

*If* Mg is applied to deficient trees *Then* root capacity may not be high enough to assimilate the Mg rapidly.

*If* Mg is applied at planting on ex farm sites *Then* fine root growth and mycorrhizal activity is stimulated.

*If* serpentine is applied @ 55 kg ha<sup>-1</sup> *Then* no improvement in growth or foliar Mg will occur.

*If* soil is an ex pasture soil *Then* plant available Mg is unlikely to be lower than in a forest soil.

*If* deficiency symptoms show in a grassed stand under age 5 *Then* weed control plus fertiliser is the best option. \*

*If* deficiency symptoms show up in a grassed stand under age 5 *Then* fertiliser without weed control is the worst option. \*

*If* Mg<sub>f</sub> is marginal *Then* do not add K<sup>+</sup> or NH<sub>4</sub><sup>+</sup> alone.

*If* dolomite is soil applied @ 400 kg ha<sup>-1</sup> Mg *Then* the improvement in soil Mg will still be measurable after 5 years.

*If* MgSO<sub>4</sub> soil applied @ 50 kg ha<sup>-1</sup> Mg *Then* no trace will be measured in the soil after 5 years.

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